PB-214 002

DESIGN OF A PARTICULATE AERODYNAMIC TEST FACILITY

Larry W. Anderson, et al

Aerotherm Corporation

Prepared for:

Environmental Protection Agency

7 December 1971

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

BIBLIOGRAPHIC DATA SHEET

1. Report No. APTD-1158

2.

PB 214 002

4. Title and Subtitle

Design of a Particulate Aerodynamic Test Facility

5. Report Date December 7, 1971

6.

7. Author(s) Larry W. Anderson, William F. Lapson, John W. Schaefer

8. Performing Organization Rept. No. 71-43

9. Performing Organization Name and Address

Aerotherm Corporation
485 Clyde Avenue
Mountain View, California 94040

10. Project/Task/Work Unit No. 7034

11. Contract/Grant No. EHSD 71-44

12. Sponsoring Organization Name and Address

U. S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air Programs
Research Triangle Park, North Carolina 27711

13. Type of Report & Period Covered Final

14.

15. Supplementary Notes

16. Abstracts

The design is addressed to a particular set of performance specifications for the test gas which include gas velocities to 90 ft/sec, temperatures to 450 F, control of the relative humidity, and occasional testing with combustion products as the test gas. Other facility requirements become apparent as the tentative uses for the facility are reviewed. These uses include development of particulate and gas sampling procedures and instrumentation, study of basic collection mechanisms, and study of basic particle flow mechanics. Basic features of other aerodynamic test facilities are reviewed, and features which are needed in the present design are identified. The literature on other particulate research facilities is also briefly summarized. Engineering trade-offs and technical considerations are then presented, which ultimately result in decisions on the basic facility layout, size, shape, and techniques for heating, humidifying, cooling, and filling the tunnel with exhaust products and with particulate material. A detailed description of the final facility design is presented. The overall design is described, then each major component is described separately. Controls and instrumentation are described. Construction of the facility, and specification sheets for each major piece of equipment are also briefly discussed.

17. Key Words and Document Analysis. 17a. Descriptors

Air pollution
Particles
Aerodynamics
Test facilities
Design criteria
Flow rate
Temperature
Humidity
Combustion products
Heat transfer
Cooling
Instruments
Wind tunnels

17b. Identifiers/Open-Ended Terms

Reproduced by
NATIONAL TECHNICAL INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

17c. COSATI Field/Group 13B

134

vailability Statement

Unlimited

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page) UNCLASSIFIED

21. No. of Pages 134

22. Price $3.00/$0.95

FORM NTIS-35 (REV. 3-72)

USCOMM-DC

Aerotherm Project 7034

December 7, 1971

Aerotherm Final
Report No. 71-43

DESIGN OF A PARTICULATE AERODYNAMIC TEST FACILITY

by

Larry W. Anderson
William F. Lapson
John W. Schaefer

Prepared for

U.S. Environmental Protection Agency
Office of Air Programs
Research Triangle Park, North Carolina

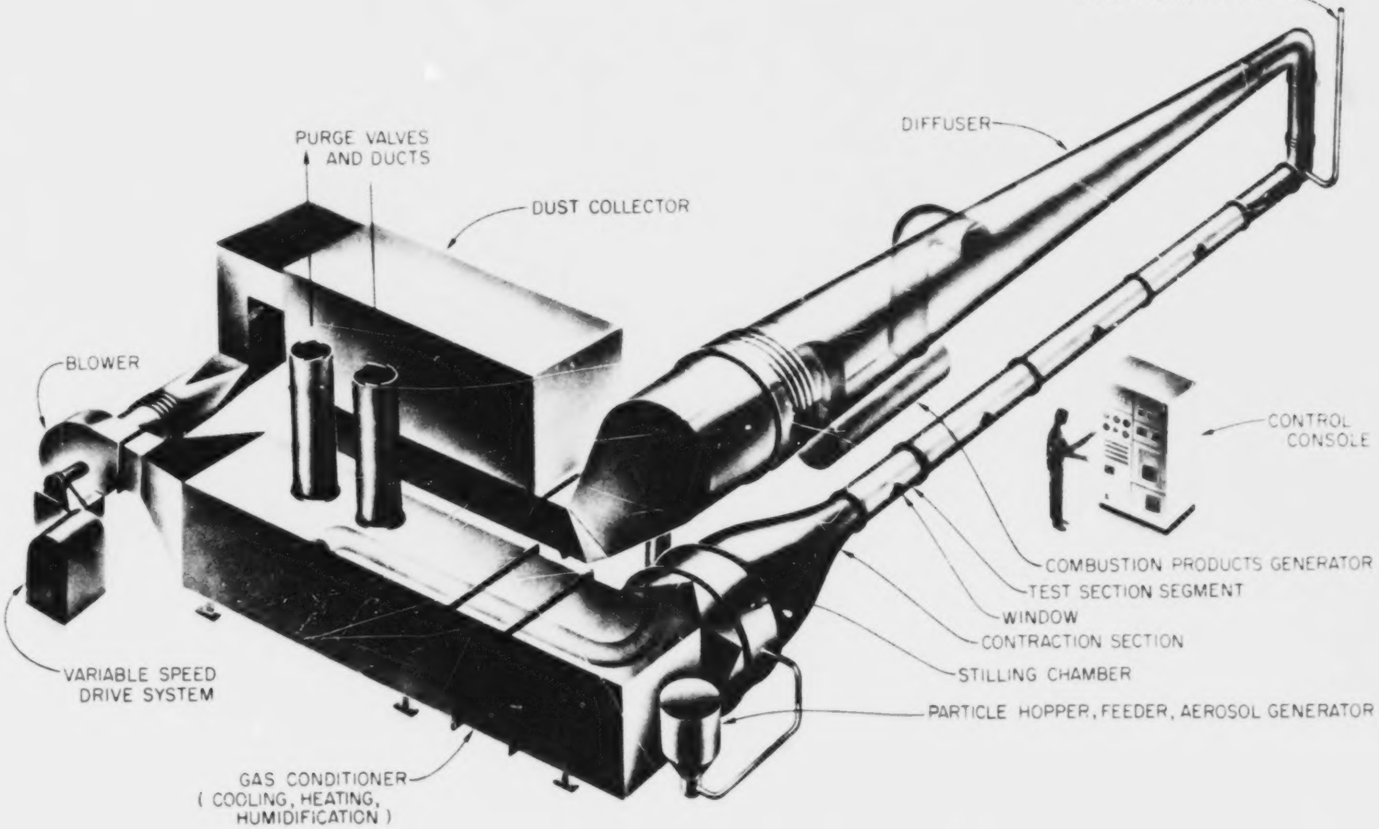
Contract No. EHSD 71-44

Technical Monitor - D. B. Harris

FOREWORD

The efforts described here were carried out for the U.S. Environmental Protection Agency, Office of Air Programs, Research Triangle Park, North Carolina, under Contract EHSD 71-44. The project was initiated by Mr. James A. Dorsey and Mr. John O. Burckle of EPA. Technical management at EPA was provided by Mr. Burckle and Mr. Bruce Harris. The assistance of these individuals in carrying out this project is gratefully acknowledged.

Dr. Larry W. Anderson was the Aerotherm program manager for the work reported here. Inclusive dates for these efforts were December 7, 1970 through October 7, 1971.


ATMOSPHERIC VENT
DIFFUSER
PURGE VALVES AND DUCTS
DUST COLLECTOR
BLOWER
CONTROL CONSOLE
COMBUSTION PRODUCTS GENERATOR
TEST SECTION SEGMENT
WINDOW
CONTRACTION SECTION
STILLING CHAMBER
PARTICLE HOPPER, FEEDER, AEROSOL GENERATOR
VARIABLE SPEED DRIVE SYSTEM
GAS CONDITIONER (COOLING, HEATING, HUMIDIFICATION)

PARTICULATE AERODYNAMIC TEST FACILITY

ABSTRACT

A design for a particulate aerodynamic test facility is presented. The design is addressed to a particular set of performance specifications for the test gas which include gas velocities to 90 ft/sec, temperatures to 450°F, control of the relative humidity, and occasional testing with combustion products as the test gas. Other facility requirements become apparent as the tentative uses for the facility are reviewed. These uses include development of particulate and gas sampling procedures and instrumentation, study of basic collection mechanisms, and study of basic particle flow mechanics.

In developing the facility design presented here, basic features of other aerodynamic test facilities are reviewed, and features which are needed in the present design are identified. The literature on other particulate research facilities is also briefly summarized. Engineering tradeoffs and technical considerations are then presented, which ultimately result in decisions on the basic facility layout, size, shape, and techniques for heating, humidifying, cooling, and filling the tunnel with exhaust products and with particulate material.

A detailed description of the final facility design is then presented. The overall design is described first, then each major component is described separately. Controls and instrumentation are described. The report is concluded with some brief remarks on construction of the facility, and specification sheets for each major piece of equipment.

TABLE OF CONTENTS

Section		Page
1	INTRODUCTION	1
2	TECHNICAL DISCUSSION	4
	2.1 Facility Requirements	4
	2.2 Basic Features of a Typical Aerodynamic Test Facility	7
	2.3 Other Existing Particulate Wind Tunnels	9
	2.4 Engineering Tradeoffs for this Facility	16
	2.4.1 Open Circuit Versus Closed Circuit Tunnel	16
	2.4.2 Horizontal Versus Vertical Test Section	17
	2.4.3 Dust Injection Technique	24
	2.4.4 Dust Generation and Metering	33
	2.4.5 Test Section Diameter and Length	42
	2.4.6 Test Gas Heating	44
	2.4.7 Air Conditioning	44
	2.4.8 Charging the Tunnel with Combustion Products	52
	2.4.9 Fan, Motor, and Speed Control	56
	2.4.10 Materials of Construction	60
3	FACILITY DESIGN	61
	3.1 General Facility Description	61
	3.2 Detailed Description of Major Components	64
	3.2.1 Fan, Motor, and Coupling	65
	3.2.2 Duct	65
	3.2.3 Gas Conditioning Section	65
	3.2.4 Duct Heater	66
	3.2.5 First Elbow	67
	3.2.6 Stilling Chamber	69
	3.2.7 Dust Feeder	69
	3.2.8 Contraction	71
	3.2.9 Test Section	73
	3.2.10 Flex Coupling Section	73
	3.2.11 Diffuser	74
	3.2.12 Elbow to Baghouse	74
	3.2.13 Baghouse	74
	3.2.14 Duct from Baghouse to Fan	75
	3.2.15 Tunnel Inlet, Exhaust, and Open Circuit Valves	75
	3.2.16 Combustion Products Burner and Firebox	78
	3.3 Controls and Instrumentation	80
	3.3.1 Control Console	80
	3.3.2 Velocity Control	82
	3.3.3 Test Gas Temperature	83
	3.3.4 Test Gas Humidity	84
	3.3.5 Test Gas Composition	84
	3.3.6 Dust Feed Rate	84
	3.3.7 Dust Carrier Gas Flow Rate	85
	3.3.8 Burner Operation	85
	3.3.9 Baghouse Cleaning Frequency	86
	3.3.10 Inlet, Exhaust and Open Circuit Valve Settings	86
	3.4 Utilities	86
	3.5 Other Design Details	87
	3.5.1 Cleanout	87
	3.5.2 Insulation	89
	3.5.3 Laboratory Housing	89
	3.5.4 Effluents	89
	3.5.5 Air Exchange Requirements	91
4	FACILITY CONSTRUCTION	92
5	SPECIFICATIONS	96
	REFERENCES	101
	APPENDIX	A-1

Preceding page blank

LIST OF FIGURES

Figure		Page
1	Floor Space Available at Durham Facility	6
2	Open and Closed Circuit Wind Tunnels	8
3	Combustion Engineering Particle Injection Technique	10
4	Approximate Plan View of Battelle Tunnel	12
5	Battelle Particle Injection System	13
6	Details of Habibi's Automotive Sampling System	15
7	Hot Gas System-Burner Source, Open Loop	18
8	Fuel Requirements for Heating an Open Circuit Flow	19
9	Cooling Water Requirements for Open Circuit Flow	20
10	Schematic Diagram of Major Components of Test Facility	21
11	Stokes Flow Particle Sink Rate	23
12	Schematic of Wind Tunnel Showing Dust Handling Equipment	25
13	Dust Flow Rate Requirements	27
14	Typical Carrier Gas Dust Loading	29
15	Turbulence Levels Downstream of Dust Injectors	32
16	Fluidized Bed Aerosol Generator	34
17	Vibrating Hopper with Regulated Output	35
18	Screw Feeder	36
19	Vaned Impeller Metering Device	37
20	Belt Feeder	39
21	Rotating Disc Feeder	40
22	Boundary Layer Growth in the Test Section	43
23	Closed Circuit Test Gas Heating Methods	45
24	Psychrometric Chart	48
25	Typical Air Conditioning System	49
26	Rotating Drum Adsorbent Dehumidifier	51
27	Tunnel Operation During Combustion Gas Pre-Charge Period	53
28	Mole Fraction of Combustion Products in Tunnel Gas as a Function of Time for Various Burner Products Flow Rates	55
29	Combustion Products Injection Techniques	57
30	Dust Metering Valve	70
31	Nozzle Dust Feed System	72
32	Inlet, Exhaust, and Open Circuit Valves	76
33	Valve Arrangement for Open Circuit and Gas Filling Operations	77
34	Firebox Exhaust Duct and Valve	79
35	Access Hatches and Drain Locations	88
36	Laboratory Housing	90

LIST OF TABLES

Table		Page
1	Effect of Nozzle Size on Carrier Gas Dust Loading	31
2	Feed Rates with Various Screw Sizes	38
3	Merits of Various Dust Feeding Methods	41
4	Heater Options	46
5	Relative Humidity Values with a Chilled Water System	52
6	Types of Wind Tunnel Fan Speed Control	59
7	Wind Tunnel Heater Requirements	66
8	Heater and Control Characteristics	68
9	Equipment Specifications	97

SECTION 1

INTRODUCTION

Aerosols emitted from stationary sources constitute one of the most common and readily observable air pollutants currently being subjected to control measures. These aerosols, which are composed of solid and/or liquid* particles, originate in the fuel used in a typical combustion process, or in the pre- or post-combustion process itself. Noncombustible components of coal and oil fuels (the ash content) pass directly through the combustion zone of a burner and are emitted to the atmosphere generally in solid form, with characteristic dimensions of one-tenth to one hundred microns and larger. Sulfur and metallic trace species in the fuel oxidize during combustion to form other aerosol components. Fuel-rich combustion results in many types of condensible organics, whose state is dependent on local temperature. Dust from material handling operations can be a problem exclusive of any combustion. Many of these particulates are noxious, corrosive, or even toxic in large concentrations. Thus, the control of aerosols is seen to be desirable not only from an aesthetic point of view, but also from a property damage and health point of view.

Measures currently in use for the control of particulates concentrate both on the allowable pollutant content of the fuel (i.e., the sulfur content) and on the allowable particulate emissions at a given installation. Particulate emissions for a given process are often controlled by mechanical means, such as inertial separators, scrubbers, baghouses, and electrical precipitators. Further advancement in the "particulate control" state of the art will require basic information on the general behavior of particulates in flue gases. In addition, more sophisticated and automated instrumentation to test the performance of control equipment or compliance with air pollution regulations is needed. Such basic information and instrumentation will play key roles in the specification of particulate control legislation.

This report documents the results of a study to develop a preliminary or conceptual design for a particulate aerodynamic test facility. The terms "preliminary" and "conceptual" are used to indicate that final design drawings were not the objective of this effort. Rather a best design solution will be described in some detail, consistent with the specific uses and constraints imposed on the desired test facility. The facility, to be installed at EPA laboratories in North Carolina, will be used by EPA personnel to study particulate flow phenomenology and to evaluate control procedures and instrumentation. More specifically, this will involve:

---

*With the exception of water, which is not considered a pollutant.

- Basic particle flow research
    1. Laser holography of particle trajectories
    2. Particle condensation, precipitation, and nucleation studies
    3. Alteration of particle diffusion rates
- Development and calibration of instrumentation
    1. Probe development and calibration
    2. Instrumentation development and calibration
    3. Sampling technique development
- Research on particle collection mechanisms
    1. Particle flow in magnetic fields
    2. Particle flow with large body forces
    3. Particle flow around obstacles and through sprays
    4. Particle flow in ductwork and breechings

At the present time, there is no research facility available which is large enough or versatile enough to perform the types of studies indicated above. The need for such a research facility is apparent if significant progress is to be made in the near future on particulate emission control technology and legislation.

The activities performed under this contract, in chronological order, were as follows:

- Identification of facility requirements

    The anticipated facility uses and the desired facility specifications were reviewed and revised with EPA personnel. The literature was reviewed for descriptions of related types of research facilities, and visits were made to several of these. Interviews with facility operators, designers, and particle flow researchers were particularly useful. Preliminary engineering calculations were made for sizing purposes, and major facility components were identified.

- Preliminary facility design

  Numerous configuration tradeoff studies were carried out, with consideration given to the allowable floor space and the type of tests to be run. Preliminary designs for major facility components and an overall facility layout were prepared and reviewed with EPA personnel.

- Detailed facility analysis and design

  A detailed analysis of each major facility component, and of the system as a whole, was conducted. Discussions with equipment vendors were held, and final selections of components were made. Conceptual designs were finalized.

- Drawings and specifications

  Final "outline" drawings of the test facility and of each major component were prepared. Utilities and control circuitry were also specified. Equipment specification sheets, including estimated costs and typical vendors, were prepared.

The remainder of this report is organized as follows. Section 2 is a general technical discussion of this facility, the facility requirements, the basic features of a typical wind tunnel facility, other particulate research facilities, and engineering tradeoffs and design calculations for this facility. Section 3 is a technical description of the proposed facility, including the overall layout, each of the major components, the controls and instrumentation, utilities, and other design details. Section 4 presents some brief construction considerations, while Section 5 includes specification sheets for the tunnel components.

SECTION 2

TECHNICAL DISCUSSION

The purpose of this section of the report is to present some of the rationale for the selected facility design. The facility requirements are reviewed, as are the basic features of a modern wind tunnel. Other existing test facilities of a related nature are described. Engineering tradeoffs and calculations are then presented to justify some of the decisions which were made.

2.1 FACILITY REQUIREMENTS

The requirements of this test facility were iterated somewhat during the course of this contract as information on sizes, costs, materials, etc. became available. The final set of requirements are as follows:

Conditioned Air Test Stream

The facility will operate with air as a test gas. The air temperature in the test section will be 70°-100°F with a 10-80 percent relative humidity level. Precision control of the temperature and humidity level at any intermediate setting will be provided. These test conditions will be attainable on a 24-hours-per-day, 365-days-per-year basis using the ASHRAE 99 percent climate criteria for Durham, North Carolina.

Exhaust Gas Test Stream

The facility will also generate and operate with typical power plant combustion products as a test stream. The exhaust products temperature in the test section will be 140°F to 450°F, with precision control of the gas temperature and composition provided. Exhaust products will be generated with natural gas fuel, however the natural gas supply is interruptable and an alternate fuel source will be provided.

Particulate Loading

The conditioned air or exhaust products test stream will be loaded with 0.1-5.0 grains/ft^3 of solid particulate material. The particulate material will range from 0.2-20 microns mean diameter, and will be uniformly mixed in the test gas at a known axial station in the test section. Particulate matter which may be in the laboratory air supply will be filtered out of the flow such that the test stream has a known particle material, size distribution, and loading.

Test Section

The test stream will flow through an enclosed test section of round cross-section, with a two-foot maximum internal diameter. The test section construction will allow interchangeable duct sections typical of fossil fuel combustion system breechings to be installed at several locations as an integral part of the test section. Test section length and minimum diameter will be determined as part of the design effort. The facility design should be such that a "low" freestream turbulence level will be encountered in the test section. Observation and lighting windows will be an intergral part of the test section construction, with window material of suitable quality for transmissometer or photographic data-taking. The flow velocity in the test section will be 5-90 ft/sec with precision control to any intermediate velocity setting.

Hot and Cold Operation

The facility will be capable of running in either the hot flow or cold flow mode, with a reasonably convenient method of changing from one mode to the other. The changeover need not be performed while the facility is in operation.

Exhaust Streams

Any gaseous exhaust streams from this test facility must meet local, state, federal, and EPA air pollution and safety regulations.

Controls

A single control station will be provided for the operation of this facility. Instrumentation will include all diagnostic and safety equipment typical of a combustion facility of this size.

Facility Cleanout

Means for accomplishing a rapid cleanout between tests of all flow surfaces exposed to the particulate material will be provided.

Laboratory Structure

A separate structure housing the test section, the facility controls, and the various equipment being used or undergoing tests will be specified.

The above items are the formal facility requirements. However, other requirements have become apparent during the design activity. The first and most apparent of these is the floor space allotment in the Durham facility. Figure 1 shows the space available for this facility. Ceiling height is nominally 20 feet, with numerous air conditioning and utility ducts hanging from the ceiling. Another requirement is the insulation of nearly all tunnel components for safety reasons. With a test stream temperature of 450°, the possibility of burns and

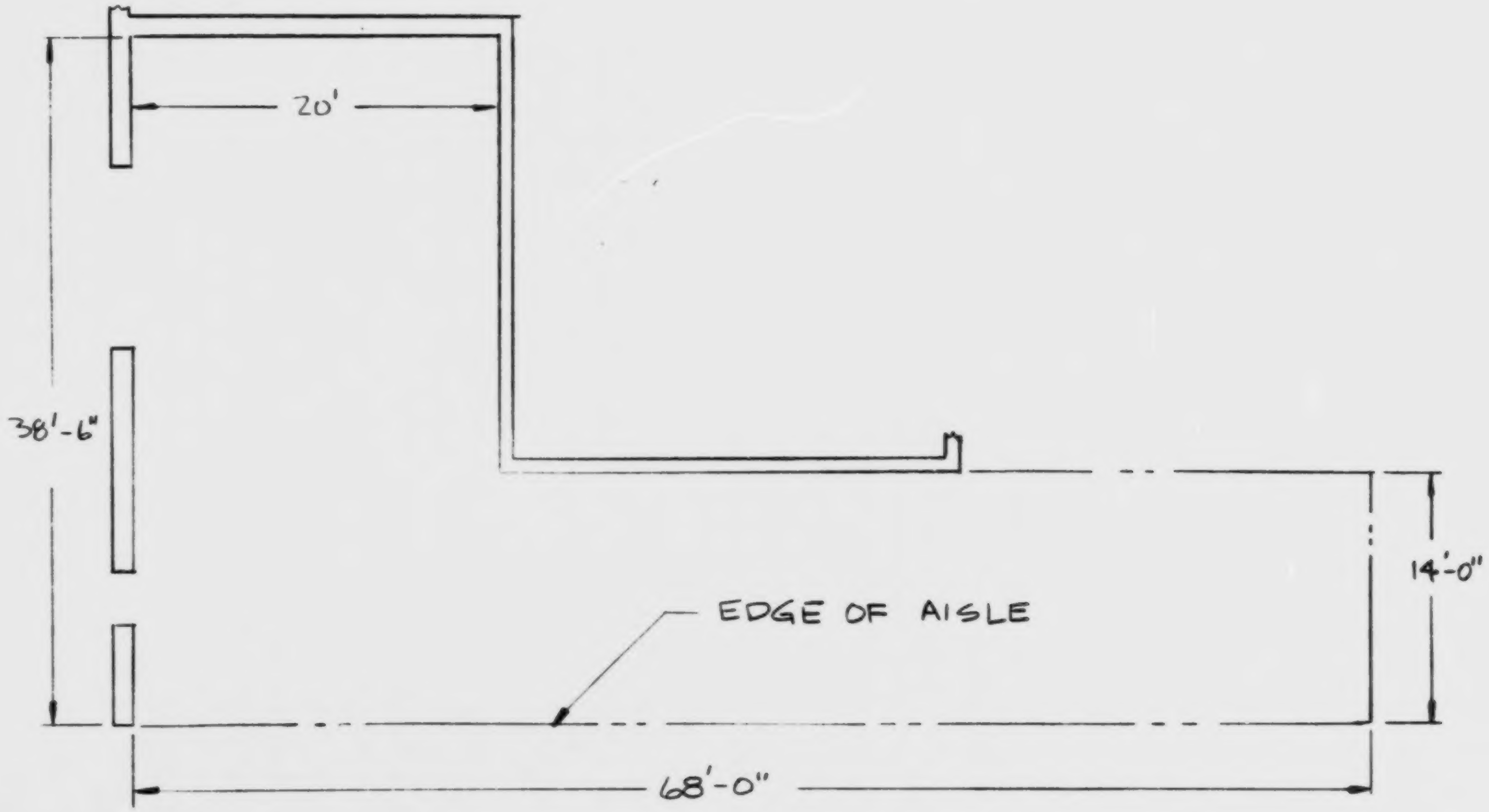

20'
38'-6"
14'-0"
EDGE OF AISLE
68'-0"

FIGURE 1 FLOOR SPACE AVAILABLE AT DURHAM FACILITY

A-3944

intense radiated heat requires that insulation be installed. Noise and vibration from the fan may also be a problem. The large capacity fan required to move nearly 17,000 scfm of air or test gas will result in very high noise levels in the vicinity of the fan, and a potential source of vibration for the supporting structure. Finally, ready access should be provided to the test section for rapid modification of probe or model setups.

2.2 BASIC FEATURES OF A TYPICAL AERODYNAMIC TEST FACILITY

An aerodynamic test facility with the test section and test gas velocity requirements described earlier is generally termed a wind tunnel. The major difference between this facility and a typical low speed wind tunnel is the requirement for a combustion products test stream and the inclusion of particulate material. Thus, it is useful at this point to review the basic features of typical low speed wind tunnels for consideration in the present facility design.

The two types of low speed tunnels in common use are the open circuit type and the single return closed circuit type, shown schematically in Figure 2. The open circuit tunnel is cheaper to build, however the closed circuit design offers better control over the test gas stream and the laboratory noise level. In the open circuit design, the blower or fan may be located downstream of the test section (as shown), or upstream at the air intake. Air proceeds through the intake, which is usually filtered, into the settling chamber. The purpose of the settling chamber is to allow turbulent eddies which may have originated in the fan or room air to settle out. To speed up this process, the settling chamber generally contains honeycomb and fine mesh screens. Air then proceeds through the contraction section, which accelerates the flow to the test section velocity through a change in cross-sectional area. There are at least two purposes for the contraction: lower pressure drop through the tunnel circuit, and lower turbulence in the test section. Since pressure drop is proportional to the square of velocity, the lower velocity in the intake and settling chamber results in significant power consumption economies. In addition, it can be shown[1] that the ratio of turbulent fluctuation to mean velocity $\sqrt{\overline{u'^2}}/U$ varies approximately as $1/n^2$ across a contraction section of area ratio n. Thus, the relative turbulence level is significantly reduced by a contraction of area ratio on the order of 10.

The size of a tunnel test section, plus the contraction ratio, determines the size of the entire test facility. The test section size is selected to accommodate any models, probes, or instruments which are to be tested with a minimum of wall interference. Test section length is generally several diameters. The walls of the test section are usually flat, and incorporate windows, lights, and access hatches to install and observe the models.

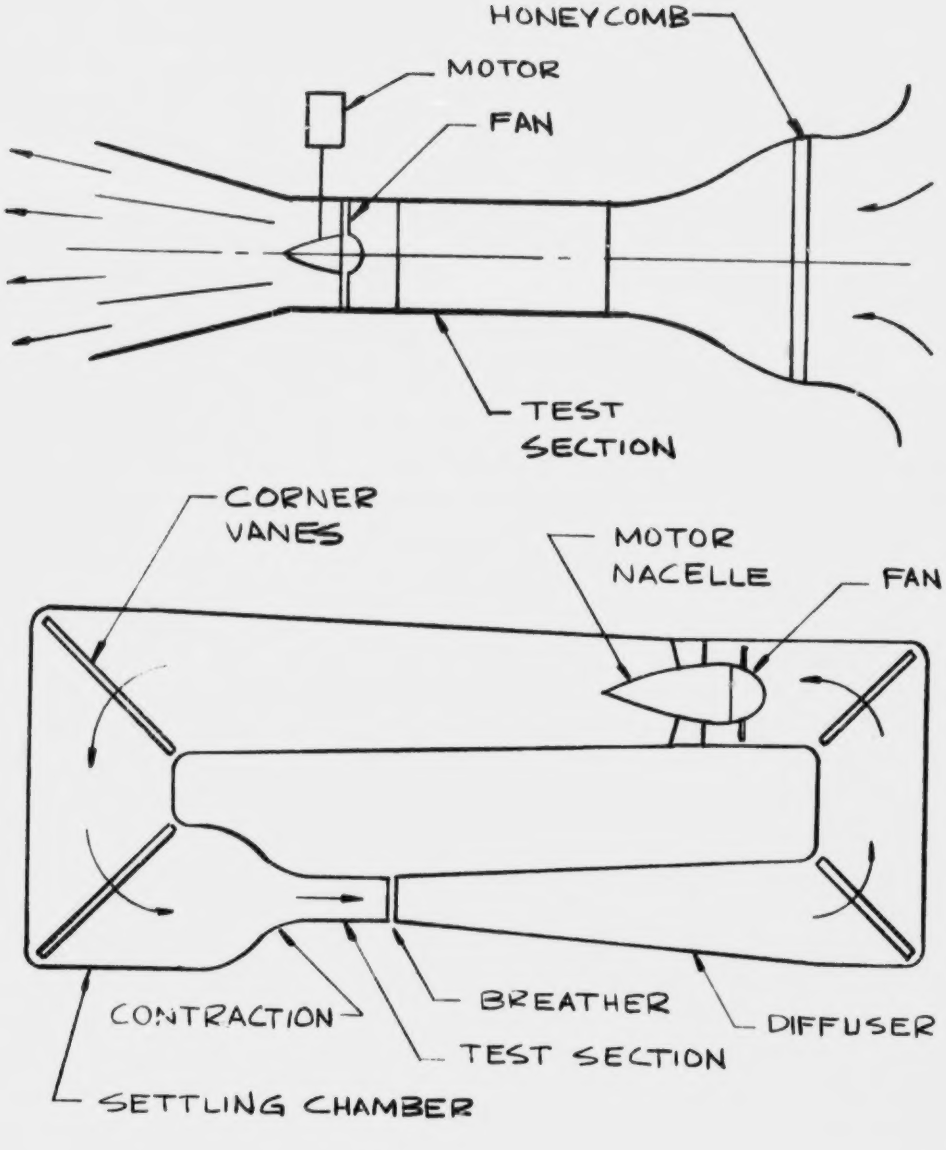

HONEYCOMB
MOTOR
FAN
TEST SECTION
CORNER VANES
MOTOR NACELLE
FAN
BREATHER
DIFFUSER
CONTRACTION
TEST SECTION
SETTLING CHAMBER

FIGURE 2 OPEN AND CLOSED CIRCUIT WIND TUNNELS

A-3945

Flow proceeds out of the test section through a diffuser. The diffuser is a gently diverging duct of approximately 5° included equivalent cone angle, however the cross section need not be round. For open circuit tunnels, the fan is generally mounted at a position in the diffuser section where cross-sectional area is about twice that of the test section. The purpose of the diffuser is to slow the flow down before exhausting it to the room, thereby minimizing both pressure drop in the tunnel and disturbance to the room air.

The design of a closed circuit tunnel is similar to the open circuit type. A settling chamber is provided which is generally one-half to two diameters in length. The contraction is extremely important in a closed circuit design as it allows low velocities in a major portion of the tunnel return circuit. The test section in a closed circuit tunnel often contains "breather" slots at the downstream end. These slots provide a controlled mass flow out of the tunnel as the recirculating air heats up, allow controlled inflow to make up for leaks elsewhere in the circuit, and keep the test section static pressure near atmospheric pressure. The return circuit is generally arranged to include four 90° turns, with turning vanes in each corner. The test stream is usually diffused as much as possible before the first turn in order to avoid large losses due to high velocity in the turn. Axial fans are most common for both open and closed circuit tunnels, however a centrifugal blower located at a corner in a closed circuit design or at either end of an open circuit design is coming into common usage[2].

2.3 OTHER EXISTING PARTICULATE WIND TUNNELS

The existing particulate wind tunnels can be classified as open circuit collector test facilities, open circuit aerodynamic test facilities, and closed circuit aerodynamic test facilities. The collector test facilities are designed to provide a controlled gas stream including particles for some type of collector, such as a scrubber. While flow velocity and particle distribution are controlled, no basic research on the gas stream itself is generally performed. Therefore high quality aerodynamic performance of this type of facility is not required for its successful operation. Johnson, et al.[3] describe a small scrubber test facility which provided a test stream 6 inches in diameter at velocities up to 65 ft/sec. Dust loadings of up to 1.0 grains/ft^3 were created with a vibrating hopper and a scraper-turntable combination dust generator. A Stairmand disc in the 6-inch supply duct resulted in a uniformly distributed dust loading at the scrubber inlet. A much larger example of this type of facility has been constructed at the Combustion Engineering Kreisinger Development Laboratory,[4] and was the object of a visit under this contract. The facility test gas is generated by an oil-fuel fired steam boiler whose sole purpose is to supply typical powerplant stack gas. The scrubber test facility handles 12,500 cfm (at 125°F). Fly ash injection is accomplished at a corner in the rectangular cross section boiler exhaust duct just upstream of a contraction, as shown in the figure below.

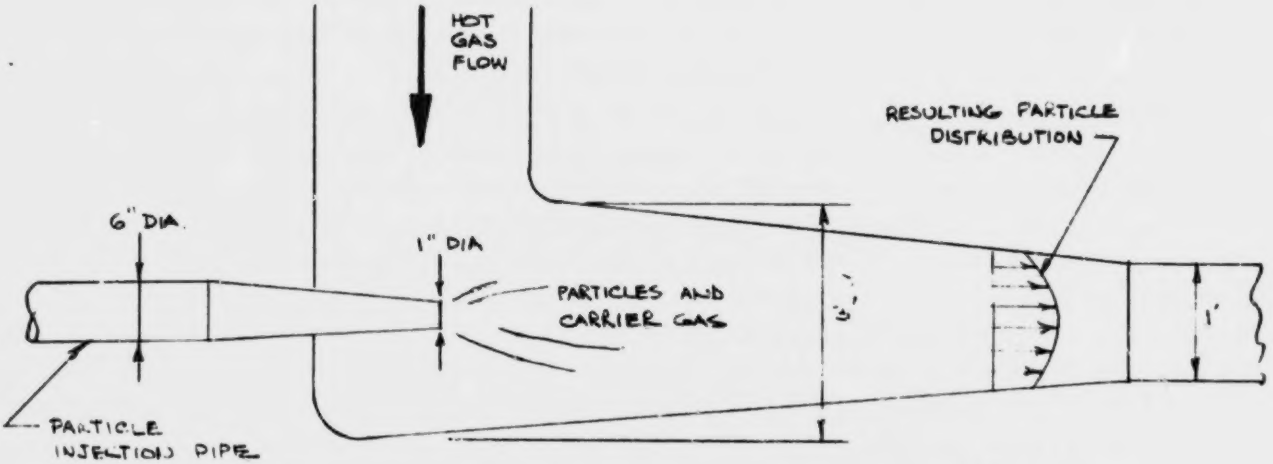


Figure 3. Combustion Engineering Particle Injection Technique.

Fly ash particles are metered and mixed with a carrier gas in conventional vibrating hopper bulk material handling equipment. The gas-particle mixture is directed through a 6-inch diameter pipe and a 1-inch diameter nozzle into the hot gas stream. Splitter vanes are included in the nozzle to direct the particles in a slightly radial direction. Final dust concentration in the duct varies approximately from 2 to 5 grains/ft^3 across the duct. More nozzles would be required to improve this concentration variation. Injection velocity is about twice the local duct velocity, although this particular variable has not been optimized. Carrier gas loading in the injection system is approximately 200 grains-dust/ft^3 gas.

The most common type of particulate aerodynamic test facility is the open circuit type. There are numerous examples of these in the literature, and only a few are discussed here. Trezak and Soo[5] worked with a small diameter (0.75 inches), blowdown-type test facility. Particles were fed into the bellmouth inlet of the 20-foot long test section which exhausted into a large volume evacuated tank system. The effects of acceleration on the two phase, high speed flow were studied. Byers and Calvert[6] studied thermopheresis effects on wall deposition using a cooled, 2-inch diameter copper tube test section. Their test gas and dust were thoroughly mixed in a baffled mixing chamber, then heated to temperatures up to 1000°F before passing into the test section. Volume flow rates up to 25 scfm were used. Work is currently underway at Lockheed Georgia[7] on a 6-inch diameter, 9-foot long test duct for use in a laser holograph flow measurement system. Gas is drawn into the duct through a 37:1 contraction ratio bellmouth and through five turbulence screens. Particles in a carrier gas are injected at the entrance to the bellmouth from a single, 1-inch diameter tube with a 1/16-inch slot along its axis. The injection tube extends across the entire bellmouth, resulting in a "sheet" of particles being injected into the flow. The actions of the screens and the contraction result in a reasonably uniform mixing of particles at the test section. Flow velocities up to 60 ft/sec are obtained using a radial blade centrifugal fan located at the downstream end of the test section.

Open circuit facilities with larger test sections have been built, but particles are generally not uniformly distributed in the flow. Lieberman[8] reports experiments conducted in a 4-foot square test section, 25 feet long. Air velocities up to 14 ft/sec were created by a downstream fan. A particle stream from a Wright dust feeder was injected isokinetically at the center of the test section. The apparatus was used to study the relative stabilities of charged and uncharged aerosols composed of 1-8μ dust particles.

An open loop tunnel at Battelle's Richland, Washington plant, designed for particle deposition studies,[9] is shown schematically in Figure 4. A personal visit to Battelle-Northwest was made to examine this facility in detail. It is an open loop, constant speed tunnel, with test section velocities of approximately 44 feet per second. This velocity can be changed by changing fan-motor pulleys. The tunnel is of the drawdown type using a centrifugal blower at the downstream end. The tunnel cross-section is square, with a 2-foot by 2-foot test section and a 6-foot by 6-foot stilling chamber, giving a 9:1 contraction ratio.

Among the good features of this tunnel are its numerous windows and white-painted internal surfaces. The large plexiglass windows provide good observation of the test surfaces, and are removable to give ready access for tunnel cleanout. The white painted surfaces combined with numerous windows make internal tunnel lighting unnecessary for observation purposes. Tunnel cleanout is accomplished by manual scrubbing with water and cleanser.

Research conducted with this tunnel involves studies of particle diffusion toward and deposition rates on various kinds of surface materials installed on one wall (the lower horizontal surface) of the tunnel test section. The particle injection technique is therefore designed to provide only this single wall with a "uniform" dust stream. Particles in a carrier gas are injected just upstream of the contraction through a 2-inch diameter pipe, as shown in Figure 5.

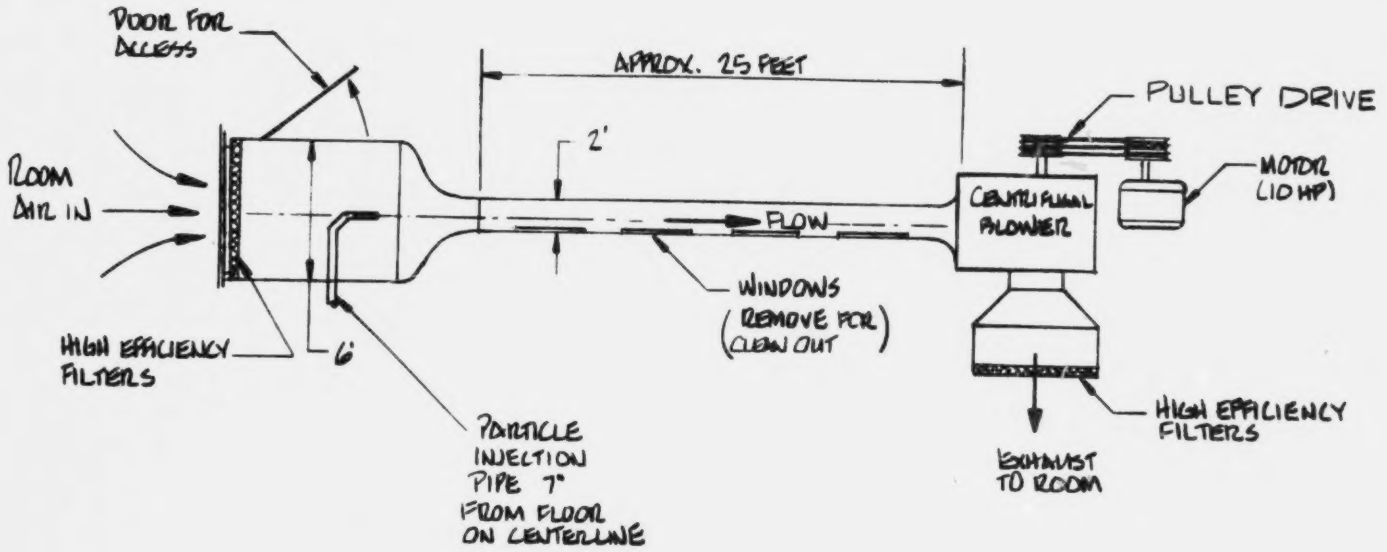

DOOR FOR ACCESS
APPROX. 25 FEET
PULLEY DRIVE
ROOM AIR IN
2'
CENTRIFUGAL BLOWER
MOTOR (10 HP)
FLOW
WINDOWS (REMOVE FOR CLEAN OUT)
HIGH EFFICIENCY FILTERS
6'
PARTICLE INJECTION PIPE 7" FROM FLOOR ON CENTERLINE
EXHAUST TO ROOM
HIGH EFFICIENCY FILTERS

FIGURE 4 APPROXIMATE PLAN VIEW OF BATTELLE TUNNEL

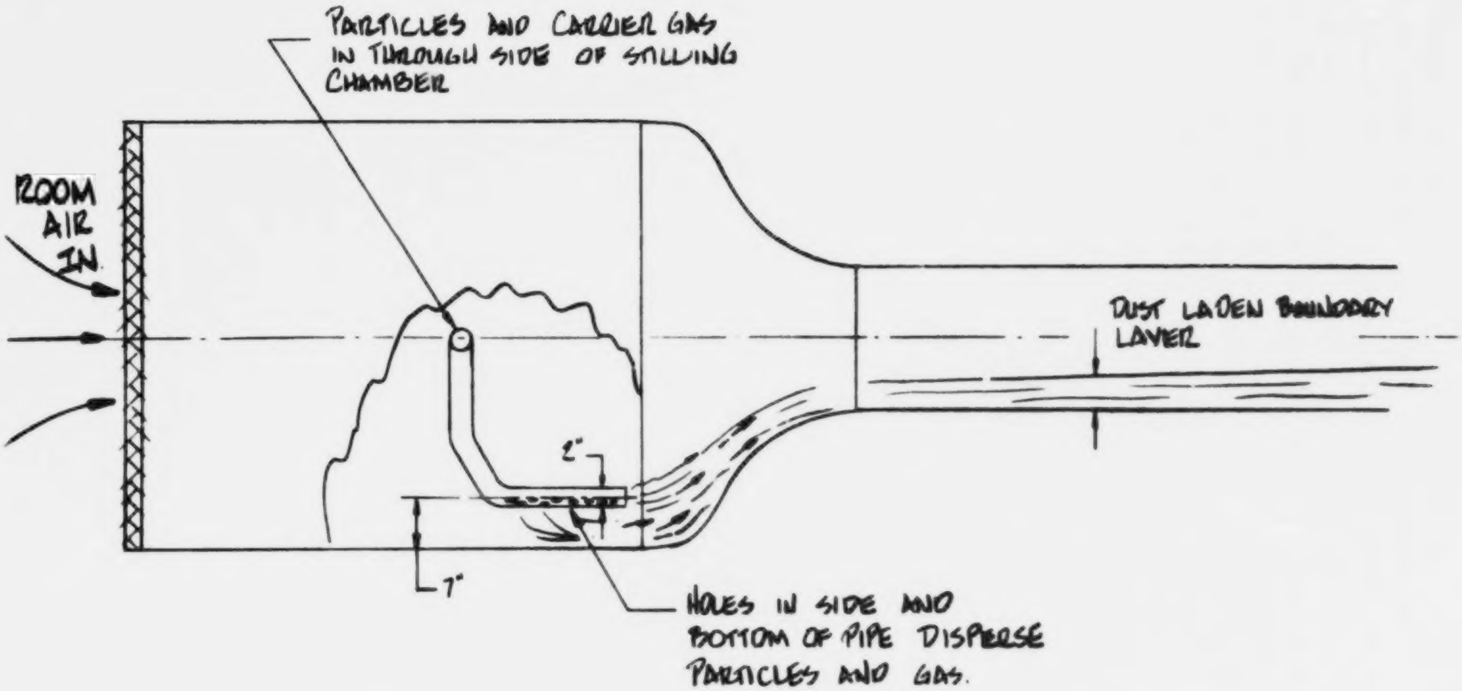

PARTICLES AND CARRIER GAS IN THROUGH SIDE OF STILLING CHAMBER
ROOM AIR IN
DUST LADEN BOUNDARY LAYER
2"
7"
HOLES IN SIDE AND BOTTOM OF PIPE DISPERSE PARTICLES AND GAS.

FIGURE 5 BATTELLE PARTICLE INJECTION SYSTEM

The injection pipe is well below the tunnel centerline, therefore the particles are contained in a relatively thin layer near the surface. Particles are filtered out of the flow just before it is exhausted to the room. High efficiency filters at both the inlet and exhaust ends of the tunnel (1-inch H_2O pressure drop at each filter unit at 44 ft/sec test section velocity) are used. Particle injection is controlled by a commerically-available spinning disk atomizer which forms droplets of uranine solution, which then evaporate to form a salt particle. Air is used as a carrier gas to inject these salt particles into the tunnel.

Snyder and Lumley[10] report development of a large wind tunnel test facility designed to study particle velocity autocorrelation functions in grid-generated turbulence. A centrifugal blower at the upstream end of the flow system supplies filtered air to a plenum chamber. The air then passes through a contraction to a test section whose dimensions are nominally 16" x 16" x 6'. One wall of the test section is adjustable to allow pressure gradient control. Also, the test section is oriented vertically to align the particle mean velocity vector with the gravity vector. Discrete particles are injected through a single 3/16-inch diameter tube at isokinetic speeds. The particle injection stream was found to have no effect on the tunnel turbulence level at distances greater than 41 inches downstream of the injection point.

A final example of an open circuit particle tunnel to be discussed here is Habibi's[11] automotive particulate sampling system. The system, shown schematically in Figure 6, consists of a filtered inlet, a 22-inch diameter by 40-foot long test section, and an 1150 cfm blower at the downstream end. Automotive exhaust containing particulate material is introduced at the upstream end of the test section. In order to promote mixing between the exhaust gas and the main air stream, the automotive exhaust is introduced at the center of a large orifice plate. The rapid spreading of streamlines downstream of this orifice plate was found to enhance the gas and particulate mixing ratio considerably.

Closed circuit particulate aerodynamic test facilities are understandably less popular since recirculation of the particulate material alters its character through agglomeration, deposition, and re-entrainment. Nevertheless, there are a few examples of closed loop systems that will be discussed briefly here. Bulba and Silverman[12] experimented with a stack dust simulation facility which consisted of a 7.7-inch diameter duct flow loop. The loop was an oval shape with outside dimensions of 4 feet by 16 feet. A small contraction was built in at the particle injection point to enhance aerosol mixing rates. No turning vanes, screens, or large contractions were contained in the circuit.

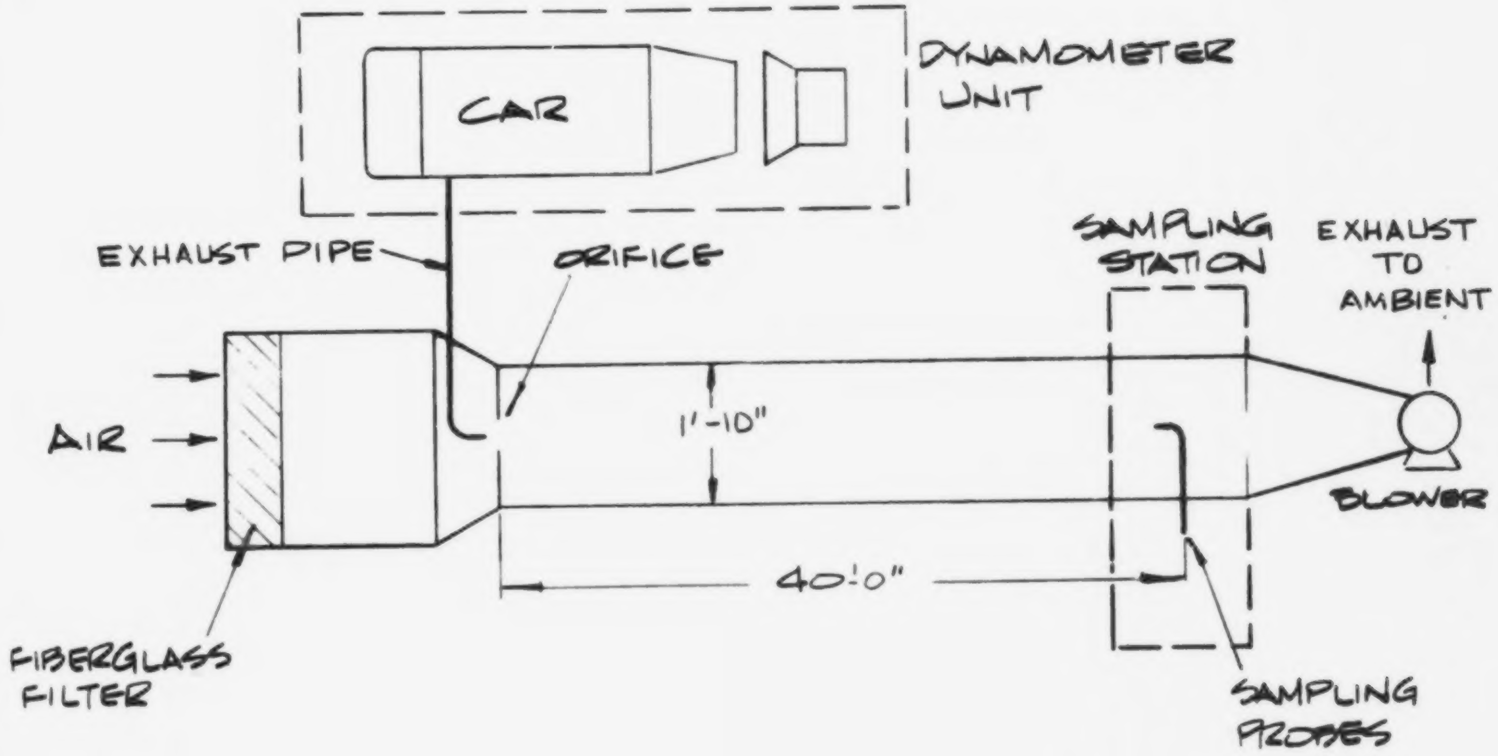

DYNAMOMETER UNIT
CAR
EXHAUST PIPE
ORIFICE
SAMPLING STATION
EXHAUST TO AMBIENT
AIR
1'-10"
BLOWER
40'-0"
FIBERGLASS FILTER
SAMPLING PROBES

FIGURE 6 DETAILS OF HABIBI'S AUTOMOTIVE SAMPLING SYSTEM

Gas velocities at the test section of 0.16 to 41.0 ft/sec were induced by a subsonic, compressed air ejector. Soo and Trezak[13] worked with a similar flow loop which used a centrifugal blower as an integral part of the loop. The test section was 5 inches in diameter and 38 feet long. Velocities of 130 ft/sec were possible with this apparatus, which was used to investigate fully developed turbulent flows with very large particulate mass loadings. The particulate material was placed in the flow loop before each test, and was cleaned out by routing the flow through a cyclone at the conclusion of a run.

The final example of a closed loop system to be discussed here is the McCrone Associates test facility[14] in Chicago. The facility was examined in detail during a visit to Walter C. McCrone Associates, Inc. under the contract. The tunnel is an oval-shaped flow loop with outside dimensions of approximately 30' x 10'. The ductwork is primarily 2'0" diameter round galvanized sheet metal duct, however a 2'0" x 2'0" square cross-section test section can be inserted. An axial fan is built into the flow circuit, as is a 250,000 Btu/hr heater. The heater combined with fiberglass insulation on the outside surface of the duct allows the test gas to reach temperatures of up to 400°F. Steady state temperature of the flow with the heater shut off but at the maximum velocity of 100 ft/sec is approximately 200°F. This high temperature is caused by the dissipation of fan power (20 HP) in the flow circuit. Particulate material is placed in the duct at the beginning of a run and circulates throughout the loop. This particulate material is cleaned out by dumping approximately 20 gallons of water into the duct with the fan in operation.

The above survey of particulate test facilities and wind tunnels is admittedly incomplete in that it does not include any of the meteorological research tunnels in existence. It does provide, in part, the basis for the necessary tradeoff considerations for the facility of interest here. These tradeoffs are presented in the following section.

2.4 ENGINEERING TRADEOFFS FOR THIS FACILITY

There are a number of preliminary tradeoffs and engineering decisions that must be made before specific wind tunnel component design activity can get underway. Several of these tradeoffs and decisions are discussed below.

2.4.1 Open-Circuit Versus Closed Circuit Tunnel

In Section 2.2, the basic features of open and closed circuit wind tunnels were discussed. It was pointed out that the advantages of a closed circuit were better control over the test stream and a much lower noise level. On the other hand, a closed circuit tunnel is more expensive to build and requires much more floor space. In choosing the best approach for the current facility design, these facts must be weighed in light of the technical requirements of the tunnel.

The first technical consideration is provision of a known particulate loading in the stream. Discussions with McCrone Associates personnel, EPA personnel, and review of the Bulba and Silverman work[12] have indicated that a closed circuit particulate flow would not be satisfactory due to agglomeration, wall deposition, and particle fracture. In addition, deposition on and erosion of fan blades is a consideration. These undesirable processes in a recirculating particulate flow will result in an unknown particle size and concentration. Therefore at least the particulate flow must be open circuit.

Another technical requirement is the need for a heated combustion products flow. Open circuit operation with combustion products would involve generation of the test gas through combustion, then cooling it to the desired test section temperature. A schematic diagram of the flow path is shown in Figure 7. To estimate the size of the components in this system, a 2-foot diameter test section was assumed. Also assuming that all the test gas comes from the burner, and that a 20:1 A/F ratio is satisfactory, the fuel flow rate requirements are shown in Figure 8. The maximum fuel flow rate of nearly 400 gallons/hour (assuming fuel oil is used) is large, but not unmanageable, assuming storage space for fuel tanks is available. A more severe limitation is the coolant required to bring the temperature of these combustion products down to the desired test section temperature. Assuming a combustion temperature of 3500°F and assuming that water is the coolant with its entire heat of vaporization available ($\Delta H_{water} \approx$ 1000 Btu/lb), the flow rate of cooling water was calculated. The results are shown in Figure 9. The maximum coolant flow rate of 120 gallons/minute is large enough that recirculation of the water coolant would be required for economy of operation. However, the associated heat exchanger and control system would be unacceptable expensive for a test facility of this size. Therefore, operation with a hot gas in an open circuit mode does not seem feasible due to its complexity and resulting high cost. Similar arguments can be made against operation in an open circuit mode in cold flow, due to the very large and expensive air conditioning system. Thus, it is concluded that closed circuit operation of the test gas, and open circuit operation of the particulate material is the most desirable system. This can be accomplished by constructing an ordinary closed circuit tunnel, injecting particles ahead of the test section, and collecting the particles after they pass through the test section. A schematic diagram of this type of flow circuit is shown in Figure 10.

2.4.2 Horizontal Versus Vertical Test Section

The study of aerosols may involve the consideration of body forces on the particles themselves. For large particles, often the gravitational force dominates and the particles tend to settle as they flow along. The settling

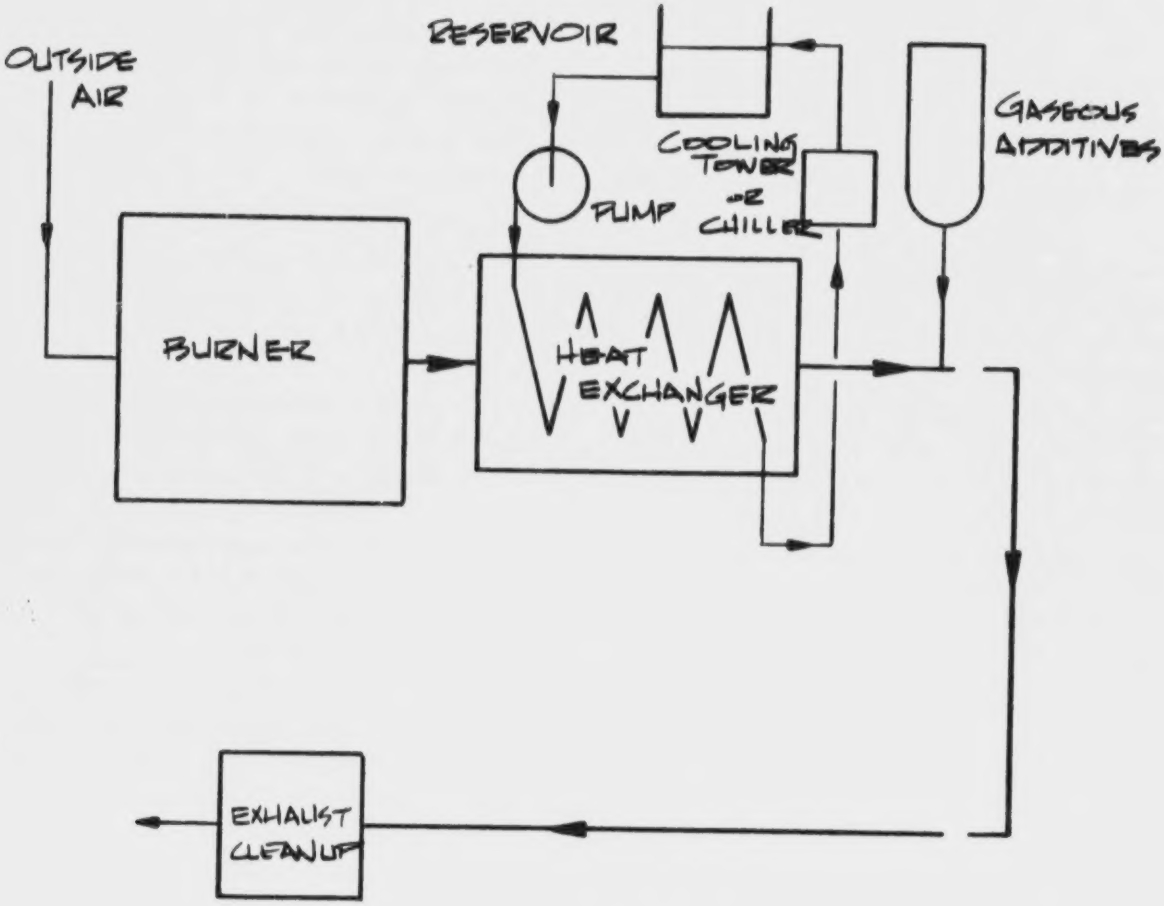

RESERVOIR
OUTSIDE AIR
GASEOUS ADDITIVES
COOLING TOWER OR CHILLER
PUMP
BURNER
HEAT EXCHANGER
EXHAUST CLEANUP

FIG 7 HOT GAS SYSTEM - BURNER SOURCE, OPEN LOOP

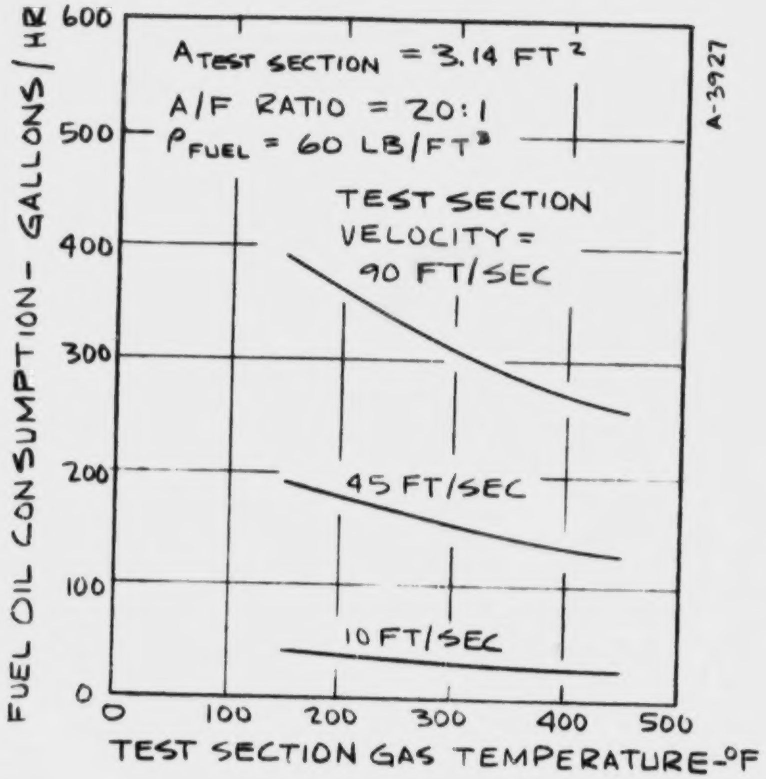


FIGURE 8 FUEL REQUIREMENTS FOR HEATING AN OPEN CIRCUIT FLOW

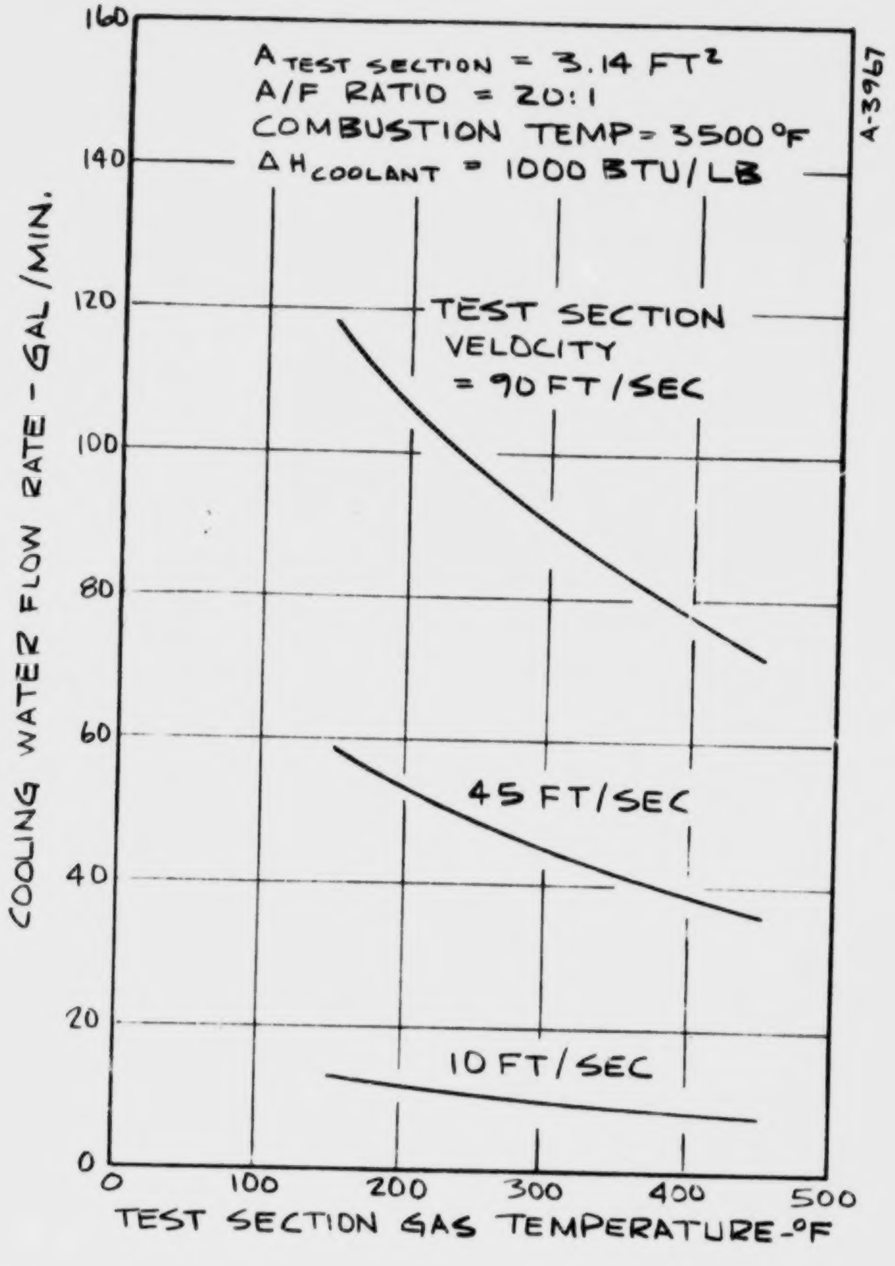


FIGURE 9 COOLING WATER REQUIREMENTS FOR OPEN CIRCUIT FLOW.

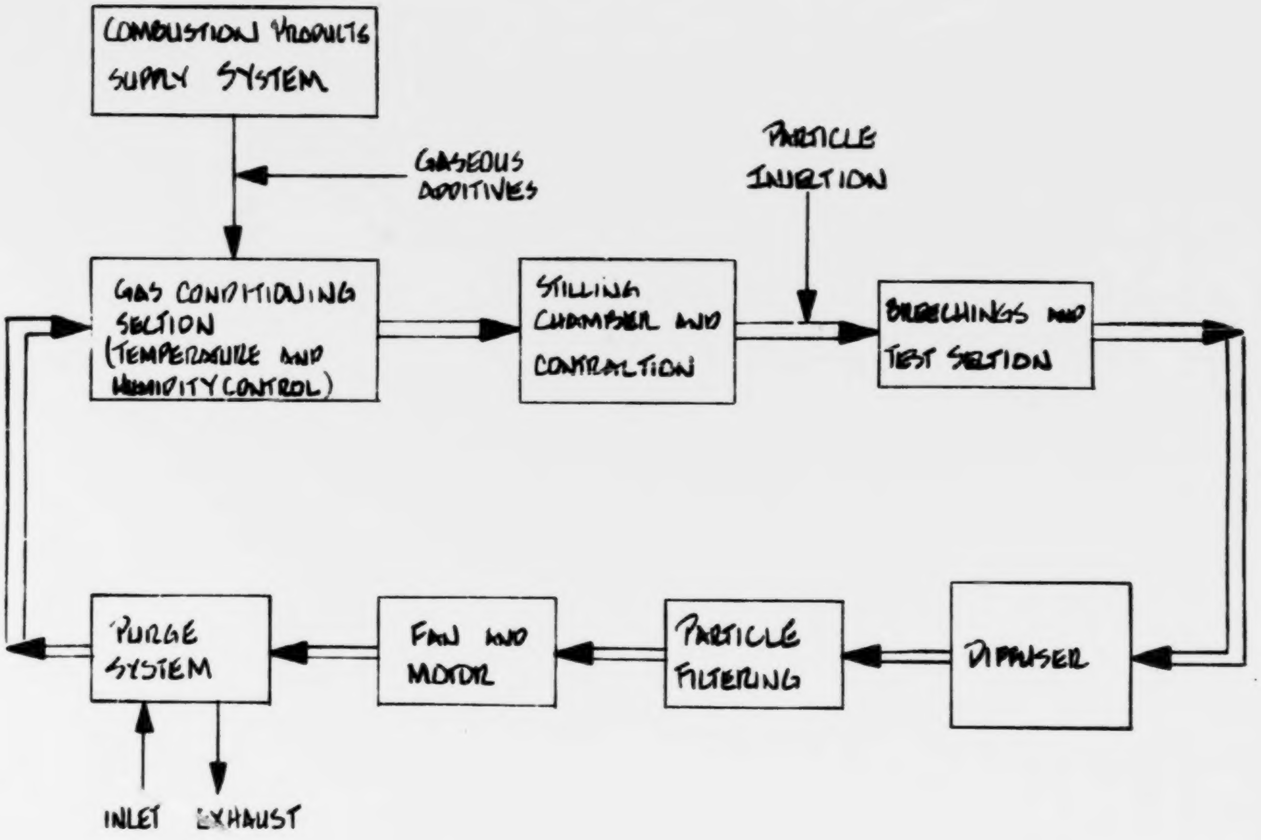

COMBUSTION PRODUCTS SUPPLY SYSTEM
GASEOUS ADDITIVES
GAS CONDITIONING SECTION (TEMPERATURE AND HUMIDITY CONTROL)
STILLING CHAMBER AND CONTRACTION
PARTICLE INJECTION
BREECHINGS AND TEST SECTION
DIFFUSER
PARTICLE FILTERING
FAN AND MOTOR
PURGE SYSTEM
INLET
EXHAUST

FIGURE 10 SCHEMATIC DIAGRAM OF MAJOR COMPONENTS OF TEST FACILITY

direction can be made coincident with the flow direction, therefore cancelling or masking undesirable flow stratification problems in basic research situations by working in a vertical test section. However other factors point to the horizontal test section as being more practical. In this section, the various considerations are discussed and a conclusion is reached regarding horizontal versus vertical test sections.

The length of the test section in question is 20 to 40 feet. Residence time of the gas at the minimum velocity of 5 ft/sec would be 4 to 8 seconds. The sink rate of spherical particles in air can be estimated by the Stokes relation

$$u = \frac{2}{9} \frac{r^2}{\mu} (\rho_p - \rho_m)$$

where

r = particle radius

μ = viscosity

ρ_p = density of the particle

ρ_m = density of the medium

Flyash is typical of the particles of interest for this test facility, with a 10 micron particle being typical.[15] Figure 11 shows the sink rate as a function of particle size for various specific gravity values. A typical flyash specific gravity is 1.6 (Reference 16). The test section temperature effect is also shown on the graph. Settling of the particles is clearly not a problem for 1 micron particles, however it may become a problem for 20 micron particles. This settling of particles can be easily calculated; however, the use of a vertical test section appears to be an advantage for basic studies with the larger particles of interest. It would also be of interest when the vertical stack situation is being duplicated.

The arguments against a vertical test section are largely nontechnical. Perhaps the most technical argument is that flow in horizontal ducts is of practical interest, therefore research into particle deposition and flow in horizontal or inclined breechings may be desirable. The major argument against the vertical test section is its lack of flexibility. This research facility will be designed to allow rapid, easy modification of the test section and other major components in order to accommodate various types of research programs. Such modifications would be complicated immensely if the test section were vertical. Similar comments apply to installation of test models, instrumentation,

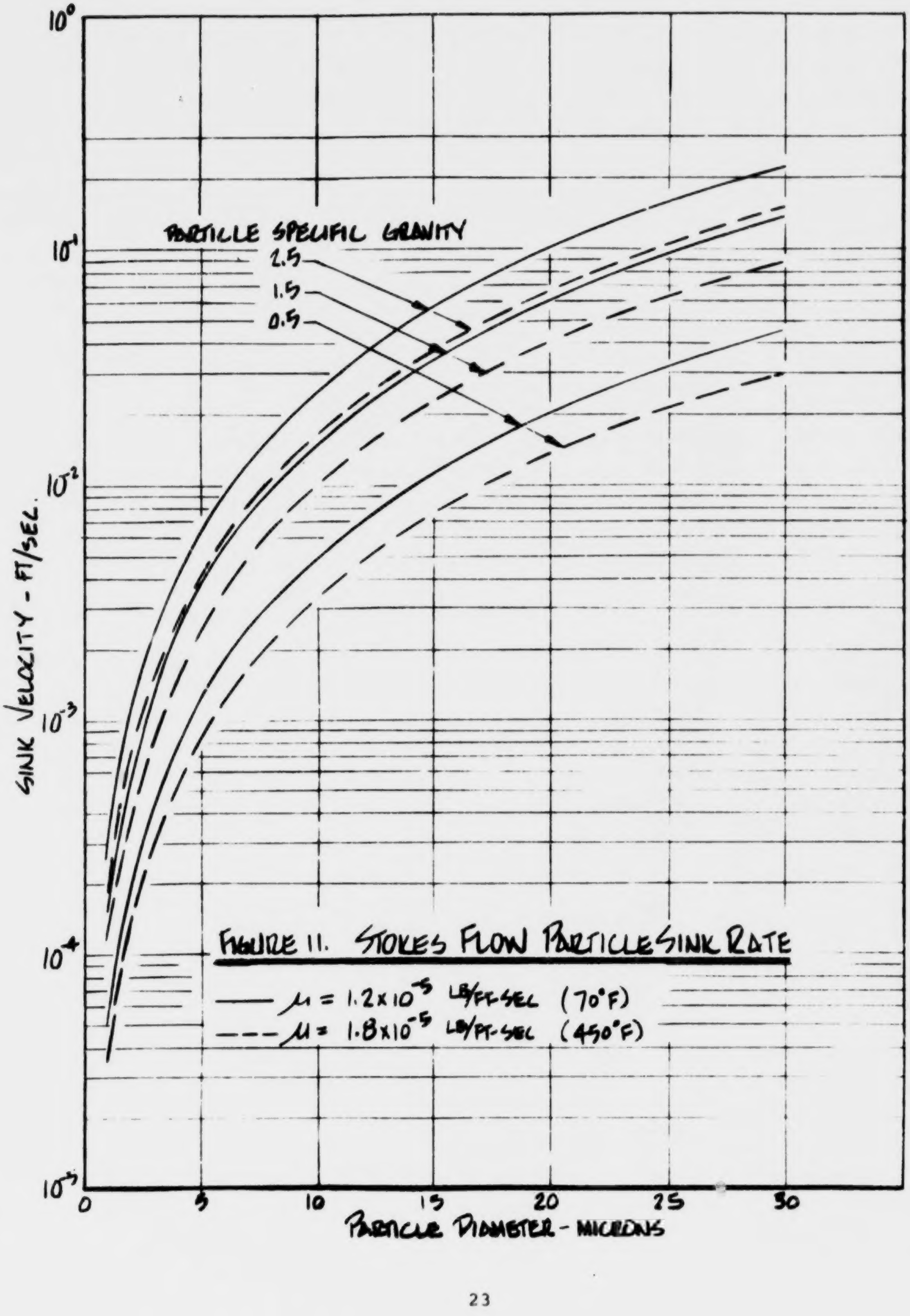


FIGURE 11. STOKES FLOW PARTICLE SINK RATE

——— $\mu = 1.2\times10^{-5}$ LB/FT-SEC (70°F)

– – – $\mu = 1.8\times10^{-5}$ LB/FT-SEC (450°F) and test observation, all of which would require frequent access to numerous stations along the test section length. The cost of research would be doubled or tripled due to the increased facility setup, running, and shutdown time. Dust cleanout would also be complicated by the need to wash down the lengthy vertical duct.

Final arguments against the vertical section involve initial cost, Bracing and other structural considerations will add to this cost significantly. An extensive scaffolding and platform system must be an integral part of a vertical duct, with means provided to install heavy equipment at numerous axial stations. In addition, major structural and architectural considerations are involved if more than about 10 feet of vertical test section was required, since the ceiling height is only 20 feet.

In conclusion, both the vertical and horizontal test sections are of interest for duplication of powerplant conditions. However, cost, convenience, and flexibility considerations indicate that a horizontal test section is a more practical selection, and a brief technical analysis indicates that technical objectives will not be seriously compromised for the particle size range of interest. Thus, a horizontal test section design is recommended for this test facility.

2.4.3 Dust Injection Technique

The wind tunnel design specification calls for a test section dust loading of 0.1-5.0 grains/ft^3 with an unspecified dust. Close control over the actual dust loading and the dust size distribution at the test section is desired. In order to allow the dust loading and size distribution to be an "independent" variable, an open circuit dust injection and collection system is called for.

As shown in Figure 12, the dust handling system includes three major components: the dust generator and metering apparatus, the dust injection apparatus, and the dust collector. Since the dust generator design is highly dependent on the injection technique, dust injection will be discussed first. Dust collection can most economically be accomplished for the high efficiencies required with a baghouse collector. Since the baghouse approach does not offer any unusual design problems, no tradeoffs will be discussed for dust collection.

a. Material Handling Considerations

Some basic engineering estimate of the flow rates, volumes, etc. will help to clarify the requirements of the dust injection apparatus. Assuming a 2'0" diameter test section, the maximum tunnel volume flow rate

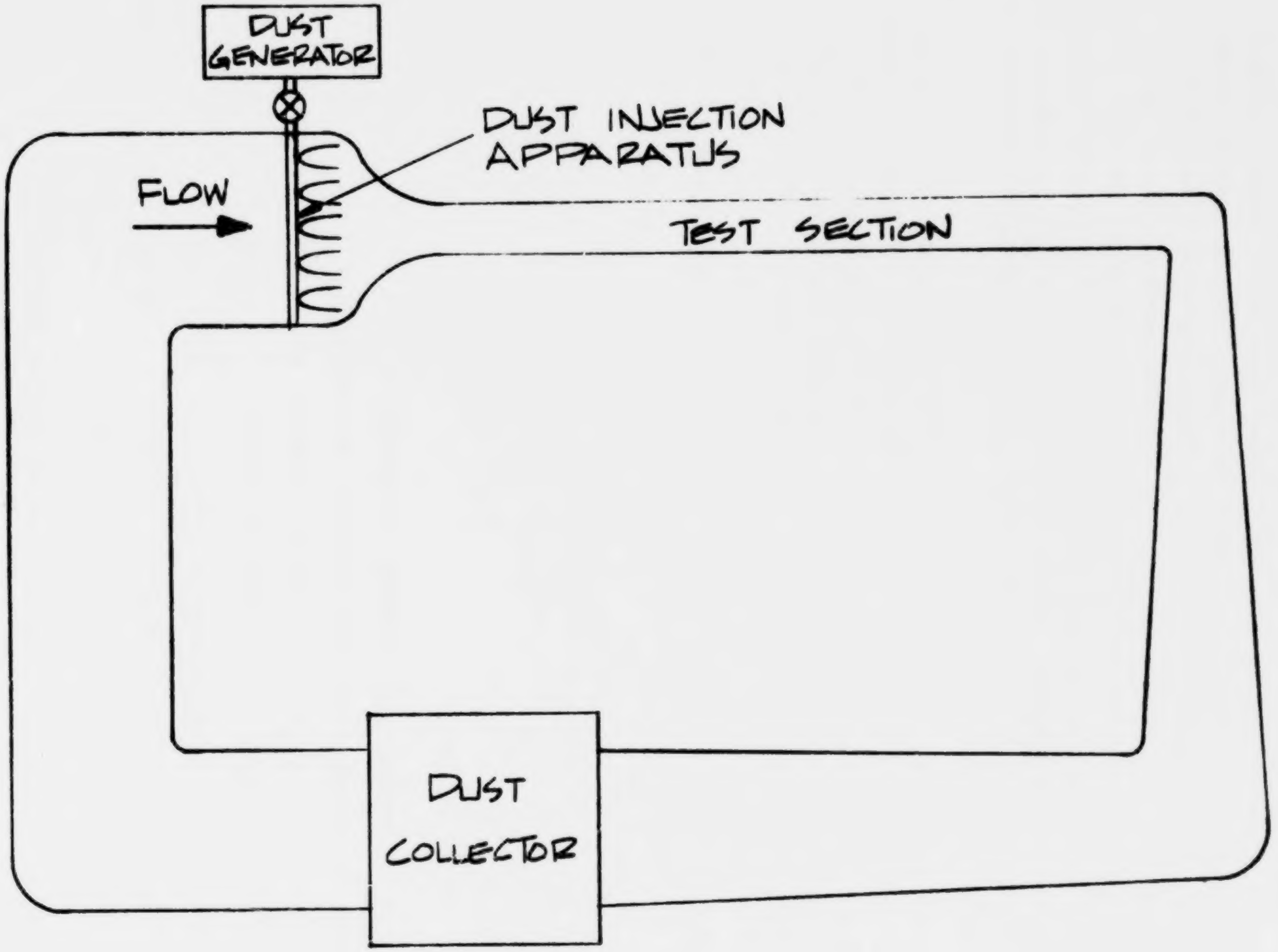

DUST GENERATOR
DUST INJECTION APPARATUS
FLOW
TEST SECTION
DUST COLLECTOR

FIGURE 12 SCHEMATIC OF WIND TUNNEL SHOWING DUST HANDLING EQUIPMENT

A-3483

is 16,980 scfm. At the maximum dust loading of 5 grains/ft^3, the injection apparatus must handle up to 12.1 lb/min of dust. Dust flow rates for other tunnel loadings are shown in Figure 13. The typical dust feeder used in plasma spray operations (Plasmadyne, Sylvester, etc.) includes a carrier gas to transport dust particles to the application point. Assuming the wind tunnel dust generator is not too unlike these machines, the maximum possible carrier gas dust loading is approximately 0.5 lb dust/ft^3 gas. Thus, at least 24.2 cfm of carrier gas will be required in the injection system for this heavy dust loading. Of course, the carrier gas loadings can be much less than 0.5 lb/ft^3, however the amount of carrier gas should be minimized to present the smallest possible disturbance to the tunnel flow.

The requirement for a low turbulence core flow in the test section along with thoroughly mixed dust is a difficult one. The use of an orifice or a Stairmand disc to accomplish dust mixing is unsuitable for this application, since either of these would introduce an unacceptable turbulence level in the tunnel. Therefore multiple injection ports, plus a significant running length must be used to achieve dust mixing.

An expression for the average tunnel dust loading for any number of jets, jet diameters, and test section conditions is

$$G = \frac{7000\ L D_j^2 U_j N}{D_t^2 U_t} \tag{2}$$

where

G = tunnel dust loading, grains/ft^3
L = carrier gas dust loading, lb dust/ft^{3}gas
D_j = injection jet diameter, inches
U_j = injection jet velocity, ft/sec
N = number of injection jets
D_t = test section diameter, inches
U_t = test section velocity, ft/sec

Choosing a 2-foot diameter test section, this expression becomes

$$G = 12.13\ L D_j^2 N \left(\frac{U_j}{U_t} \right) \tag{3}$$

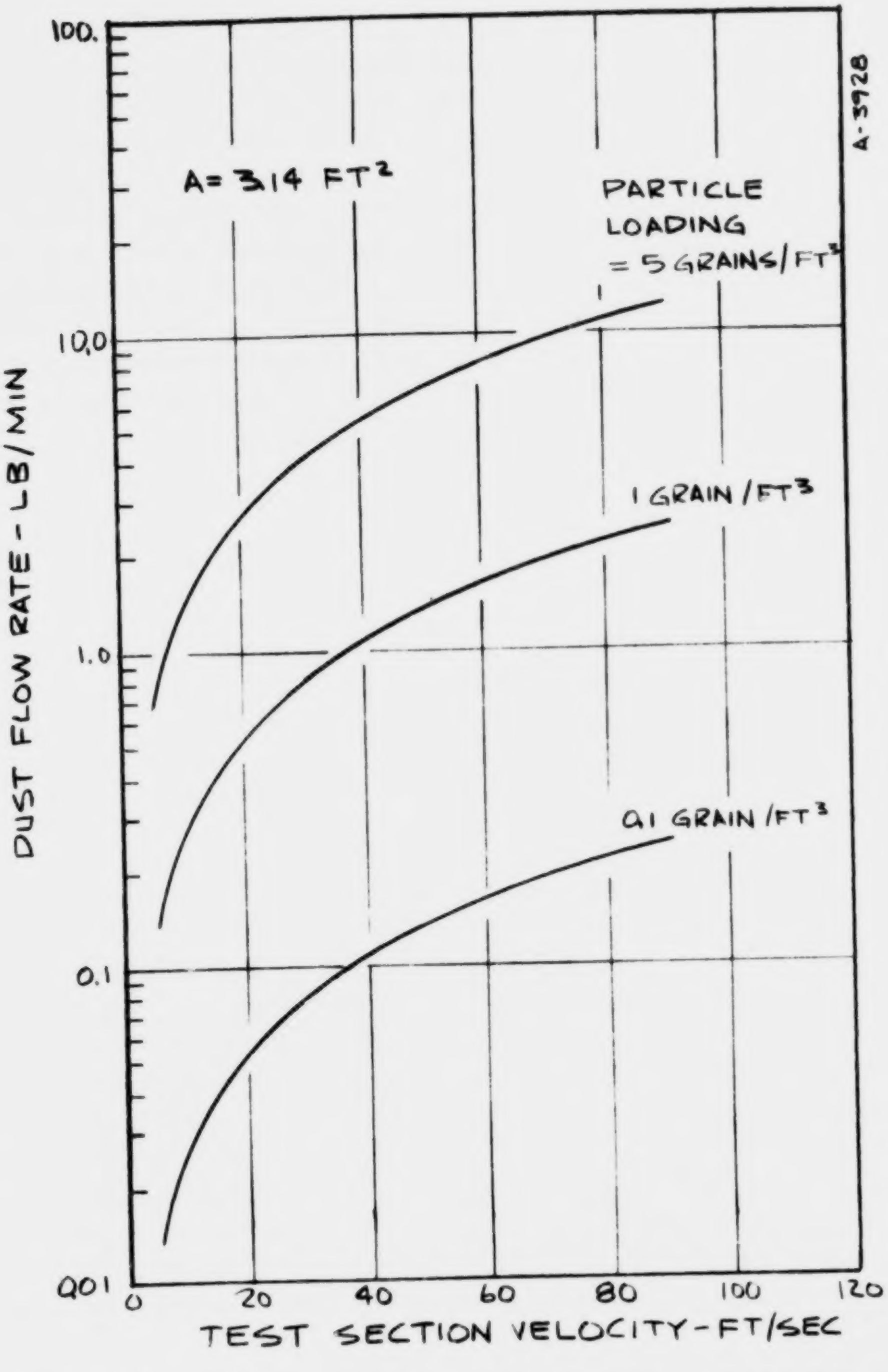


FIGURE 13 DUST FLOW RATE REQUIREMENTS

In a typical operating injection system, the number of jets and the jet diameter would be fixed, or at least it would be inconvenient to change them. When the tunnel dust loading is to be changed, the remaining injection system variables are carrier gas loading and jet velocity. These variables should be independently controlled in order to provide the desired flexibility in the dust injection system. As an example of the range of carrier gas dust loadings required, Figure 14 presents results calculated from Equation (3) assuming ten 1/4-inch diameter jets injecting dust at 1000 ft/sec. This high injection velocity corresponds approximately to a sonic injection condition, and would enhance the dust mixing rate due to the large velocity difference between the jet and the test gas stream. The desirability of injecting at high velocity is discussed in the next subsection.

b. Injection Velocity Considerations

The contract calls for a tunnel design which provides a "low" freestream turbulence level in the test section core flow. The term "low turbulence" will be taken to mean low with respect to typical powerplant stack flows. Turbulence in a stack can be expected to be on the order of fully developed pipe flow turbulence, or even larger if obstructions, wind gusts, duct transition sections, rotating air pre-heaters, etc. are encountered by the flow. Thus, a 5 percent turbulence level, i.e.

$$\frac{u_x'}{\bar{U}_{max}} \simeq \frac{u_r'}{\bar{U}_{max}} \simeq \frac{u_\phi'}{\bar{U}_{max}} \simeq 0.05^*$$

could be expected in a fully developed pipe flow[17] or stack flow. Turbulence levels are actually higher near the wall and lower near the center of a pipe, however 5 percent is a good average value. The wind tunnel should therefore have a turbulence level of 0.5 percent or less, if possible. This is not a particularly low turbulence level for aerodynamic work, where tunnels operating at a test section turbulence level of 0.1 percent are not uncommon.[18,19]

The requirement of injecting dust into the wind tunnel and mixing this dust with the primary tunnel flow directly conflicts with the need for low turbulence. Good mixing between two flowing streams generally requires high levels of turbulence in the mixing zone. This method could, in fact, be used

---

*The notation u' actually refers to $\sqrt{\overline{u'^2}}$, the root mean square velocity fluctuation value.

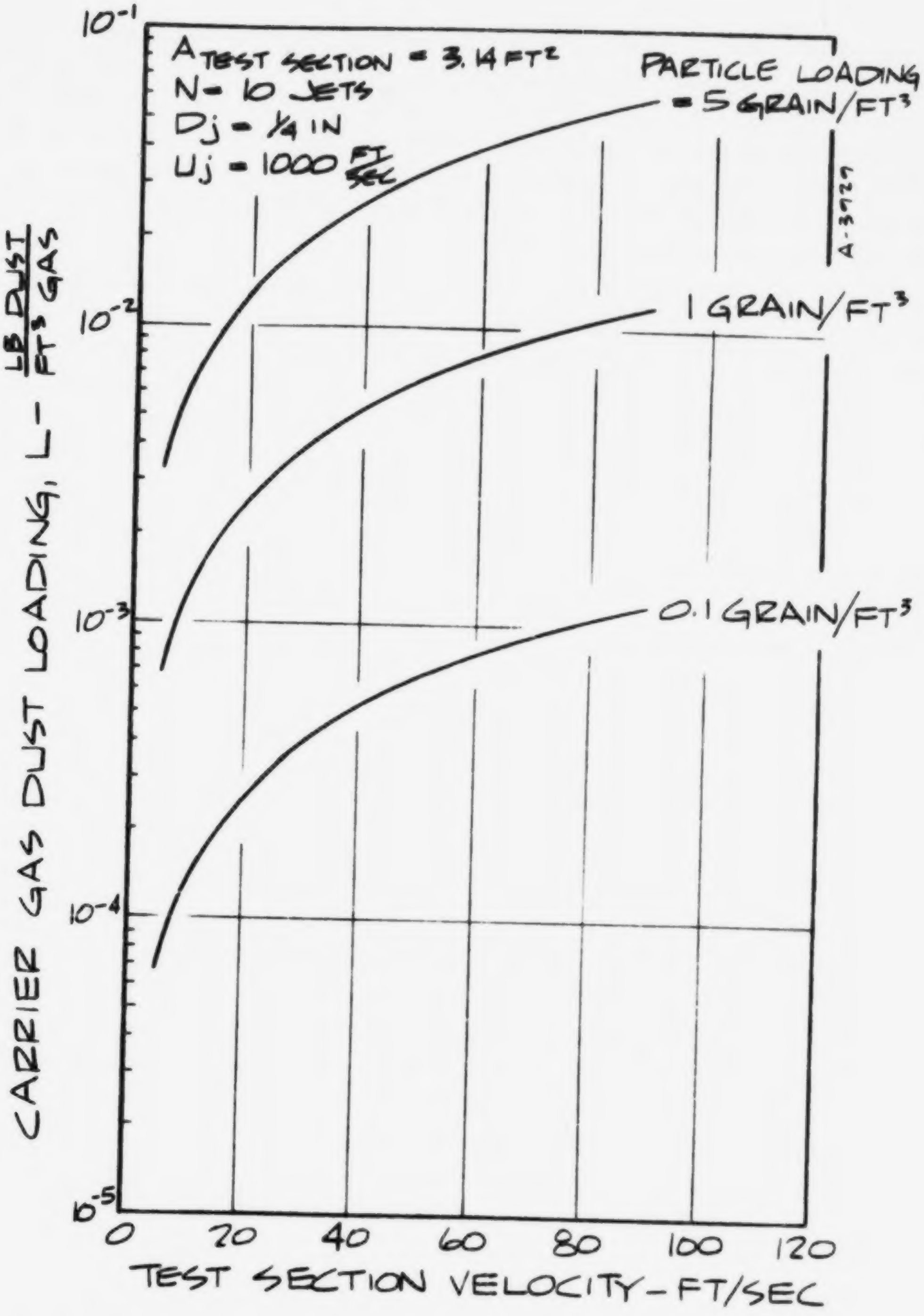


FIGURE 14 TYPICAL CARRIER GAS DUST LOADING

in this tunnel also, if dust was not the medium to be mixed. However, the removal of tunnel turbulence by conventional screens and honeycombs once the dust has been introduced is unsatisfactory in this tunnel, since the dust would collect, agglomerate, break up, and generally be altered in character by the turbulence damping devices.* Therefore the optimum point for injection of dust would be downstream of any flow obstructions, and preferably with as little generation of "new" turbulence as possible.

Generation of turbulence by the shearing action between a jet and its surrounding medium can be minimized by matching the jet velocity to the local medium velocity, known as isokinetic injection. It will be assumed that the dust velocity equals the injection jet velocity. With this approach the mixing rate is dominated by turbulence already in the mixing streams, either from initial boundary layers and wakes from the injection tubes, etc., or "freestream" turbulence. Turbulence in the test section from the injection process can be minimized by injecting upstream of the contraction. Isokinetic injection would then require that $u_j = u_t/CR$ where CR is the contraction ratio. Referring to Equation (3)

$$G = 12.13 \frac{LD^2N}{CR} \tag{4}$$

With this approach, the turn down ratio requirement on the carrier gas loading rate is greatly reduced. Operation of the dust feeder in this mode would require setting the carrier gas feed rate such that the injection velocity matches the settling chamber velocity, then setting the dust feed rates to get the necessary carrier gas dust loading. Table 1 indicates the carrier gas loadings necessary for ten injection nozzles and a contraction ratio of nine. It is clear that 1-inch diameter or larger nozzles will be needed for injection in the settling chamber.

The turbulence generated by the injection of dust at the test section velocity is expected to consist almost entirely of wake turbulence from the injection tubes. The mean square turbulent intensity downstream of a cylinder in crossflow can be estimated from the expression[20]

$$\frac{u'}{\bar{U}} = 0.27 \sqrt{\frac{D_{cyl}}{X}} \tag{5}$$

---

*This opinion has been confirmed through discussions with Lockheed/Georgia personnel,[7] who have tried this approach. It is possible to vibrate the screens and honeycomb, however, and minimize the particle deposition. This approach could be used if sufficient mixing is not obtained with the proposed approach.

TABLE 1

EFFECT OF NOZZLE SIZE ON CARRIER GAS DUST LOADING

Test Section Dust Loading (grains/ft^3)	Nozzle Diameter (inches)	Carrier Gas Dust Loading (lb/ft)^3
5.0	0.25	5.84
1.0		1.190
0.1		0.119
5.0	1.0	0.370
1.0		0.0741
0.1		0.00741
5.0	2.0	0.0926
1.0		0.0186
0.1		0.00186

Since the wake is generated at the stilling chamber velocity, the relative turbulence intensity is immediately altered by the contraction such that

$$\frac{u'}{\bar{U}} = \frac{0.27}{CR}\sqrt{\frac{D_{cyl}}{X}} \tag{6}$$

where

CR = contraction ratio

Figure 15 illustrates the resulting turbulence intensities for various distances along the tunnel, assuming a contraction ratio of nine. It is apparent that, according to this approximate analysis at least, the turbulence level will be satisfactory within a few feet of the injection apparatus. Since the contraction region is several feet long, a large portion of the test section is expected to have a suitably low turbulence level.

The remaining question of a general nature is the definition of the axial distance required for total mixing of the jets. Centerline concentrations must decay from an initial maximum 3500 grains/ft^3 down to 1-5 grains/ft^3. This is a decrease of three orders of magnitude in concentration, which is far beyond the regime described in currently available jet mixing literature. The available literature does indicate that a decrease in concentration of two orders of magnitude can be expected in the first 20-50 jet diameters. Thus, it can be speculated that another order of magnitude decay might be expected by about 200

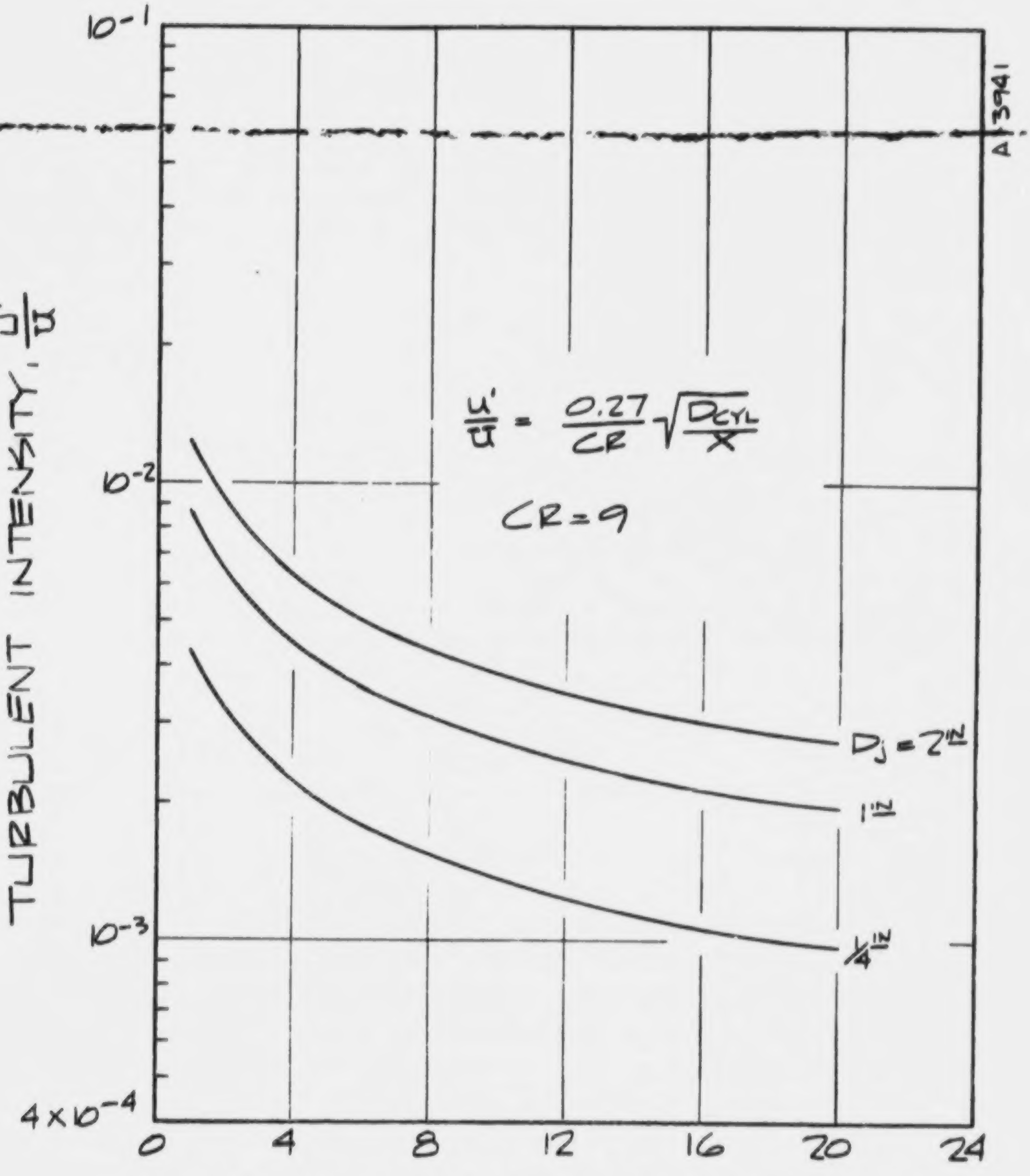


FIGURE 15 TURBULENCE LEVELS DOWNSTREAM OF DUST INJECTORS

jet diameters. This length would not be unreasonable if numerous small jets were used, and if sufficient test section length is available. However, experimentation with the actual injector configurations (preferably on a laboratory bench scale apparatus) will be necessary before the required mixing lengths can be further defined.

2.4.4 Dust Generation and Metering

The various techniques for dust metering and aerosol generation include the following:

- Fluidized bed
- Vibrating hopper with adjustable outlet orifice
- Screw feeder
- Vaned impeller
- Slotted discs, cylinders
- Belts or discs with scrapers

In this list, only the fluidized bed technique results directly in an aerosol. The other techniques are a means for metering dust into an aerosol generator, e.g., an aspirator.

A fluidized bed aerosol generator is shown in Figure 16. The dust flow rate is regulated by the fluidizing gas flow, while the condition for isokinetic injection is satisfied by diluting the aerosol to obtain the required nozzle velocity. The principle advantage of this type of generator is that mostly separated particles find their way to the outlet with large agglomerates remaining behind. More sophisticated versions of the fluidized bed using metal balls to break up agglomerates have also been developed for special applications.

A vibrating hopper with an adjustable outlet orifice is shown in Figure 17. With this arrangement, dust is shaken into an aspirator where it is aerosolized. The dust falls through a regulated orifice onto a balance, generating a feedback signal to the orifice controller. By using feedback, the feed rate can be controlled precisely.

Screws and vaned impellers (Figures 18,19) are volumetric metering devices. Thus, the rotational speed determines the delivery rate. In the case of a screw feeder, the delivery is continuous, so that one could expect to vary the delivery rate over a wide range. The impeller, however, provides a delivery which is basically intermittent - a limitation on the lower delivery rates. Feedback regulation of rotational speed could be used to overcome variations in delivery rate caused, for example, by a change in dust characteristics affecting the filling of screw or impeller cavities.

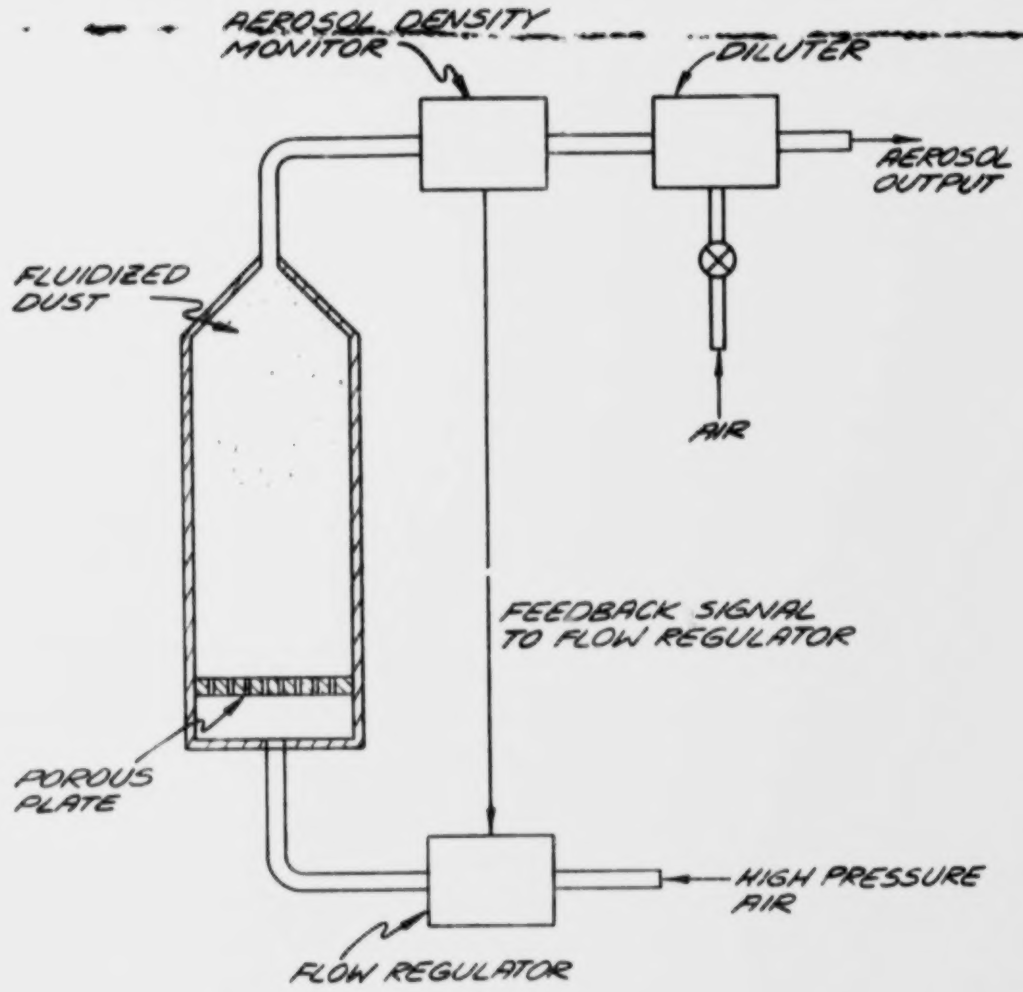

AEROSOL DENSITY MONITOR
DILUTER
AEROSOL OUTPUT
FLUIDIZED DUST
AIR
FEEDBACK SIGNAL TO FLOW REGULATOR
POROUS PLATE
HIGH PRESSURE AIR
FLOW REGULATOR

FIGURE 16. FLUIDIZED BED AEROSOL GENERATOR

A-3932

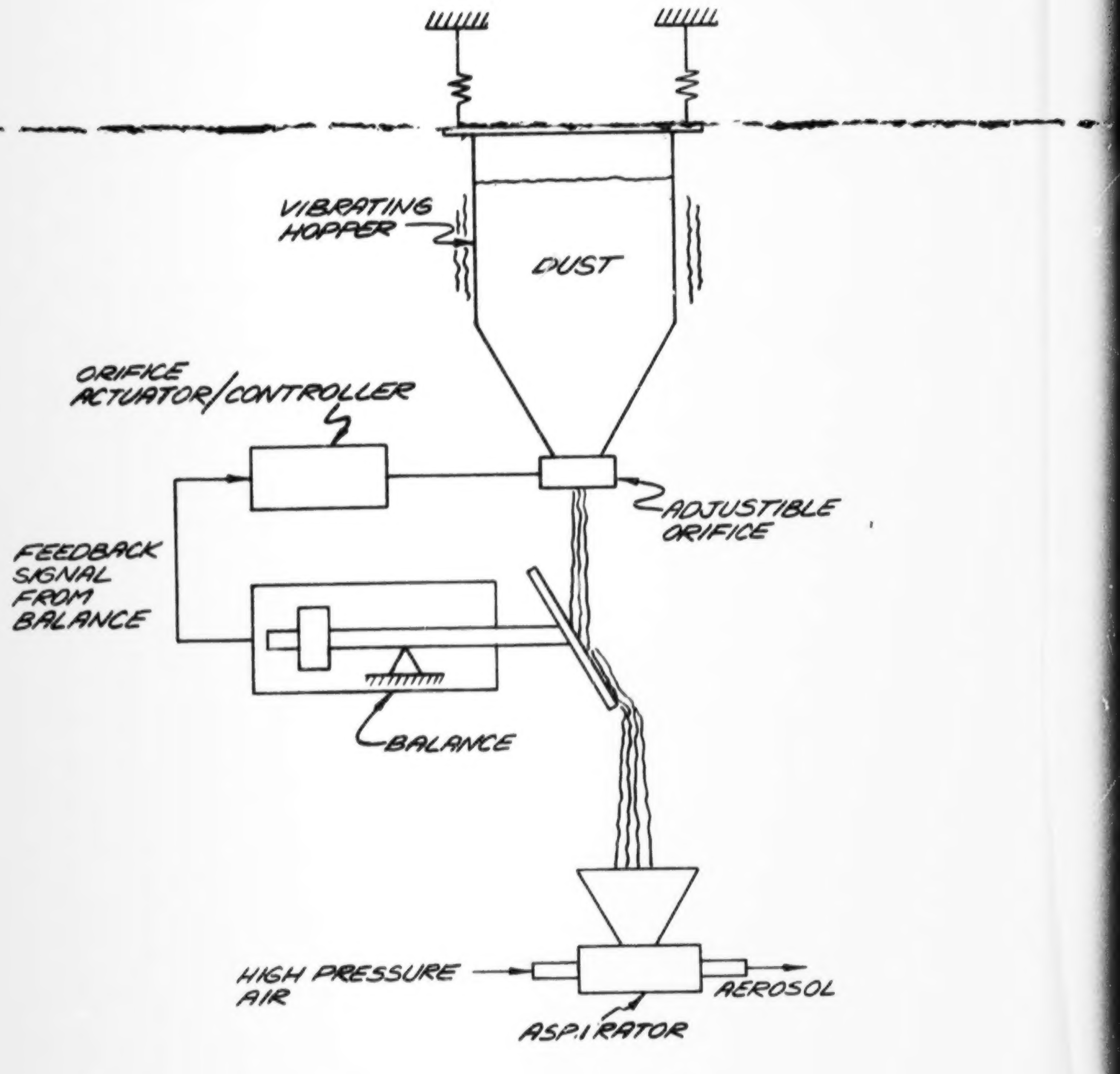

VIBRATING HOPPER
DUST
ORIFICE ACTUATOR/CONTROLLER
ADJUSTIBLE ORIFICE
FEEDBACK SIGNAL FROM BALANCE
BALANCE
HIGH PRESSURE AIR
AEROSOL
ASPIRATOR

FIGURE 17. VIBRATING HOPPER WITH REGULATED OUTPUT

A-3934

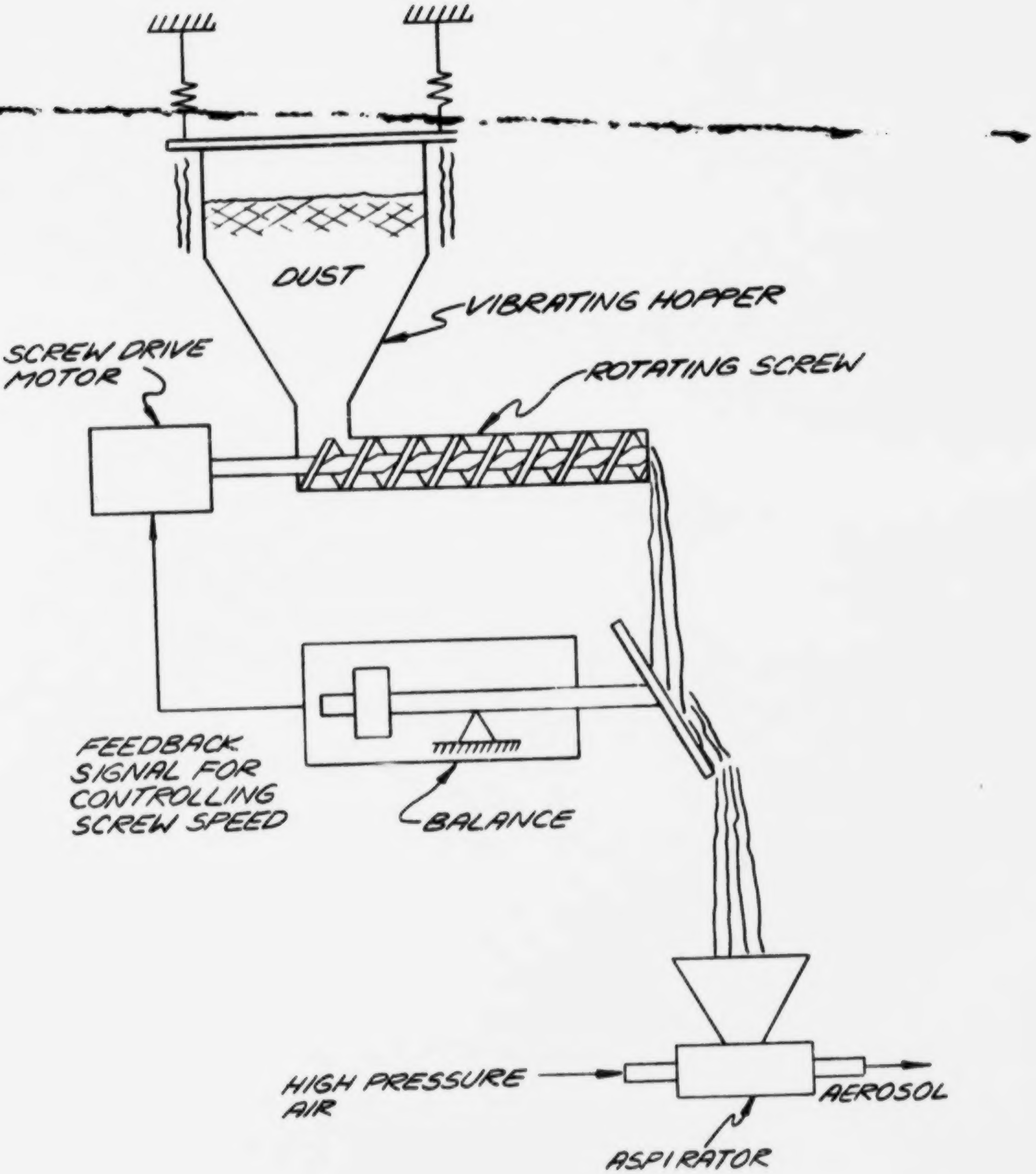

DUST
VIBRATING HOPPER
SCREW DRIVE MOTOR
ROTATING SCREW
FEEDBACK SIGNAL FOR CONTROLLING SCREW SPEED
BALANCE
HIGH PRESSURE AIR
AEROSOL
ASPIRATOR

FIGURE 18. SCREW FEEDER

A-3935

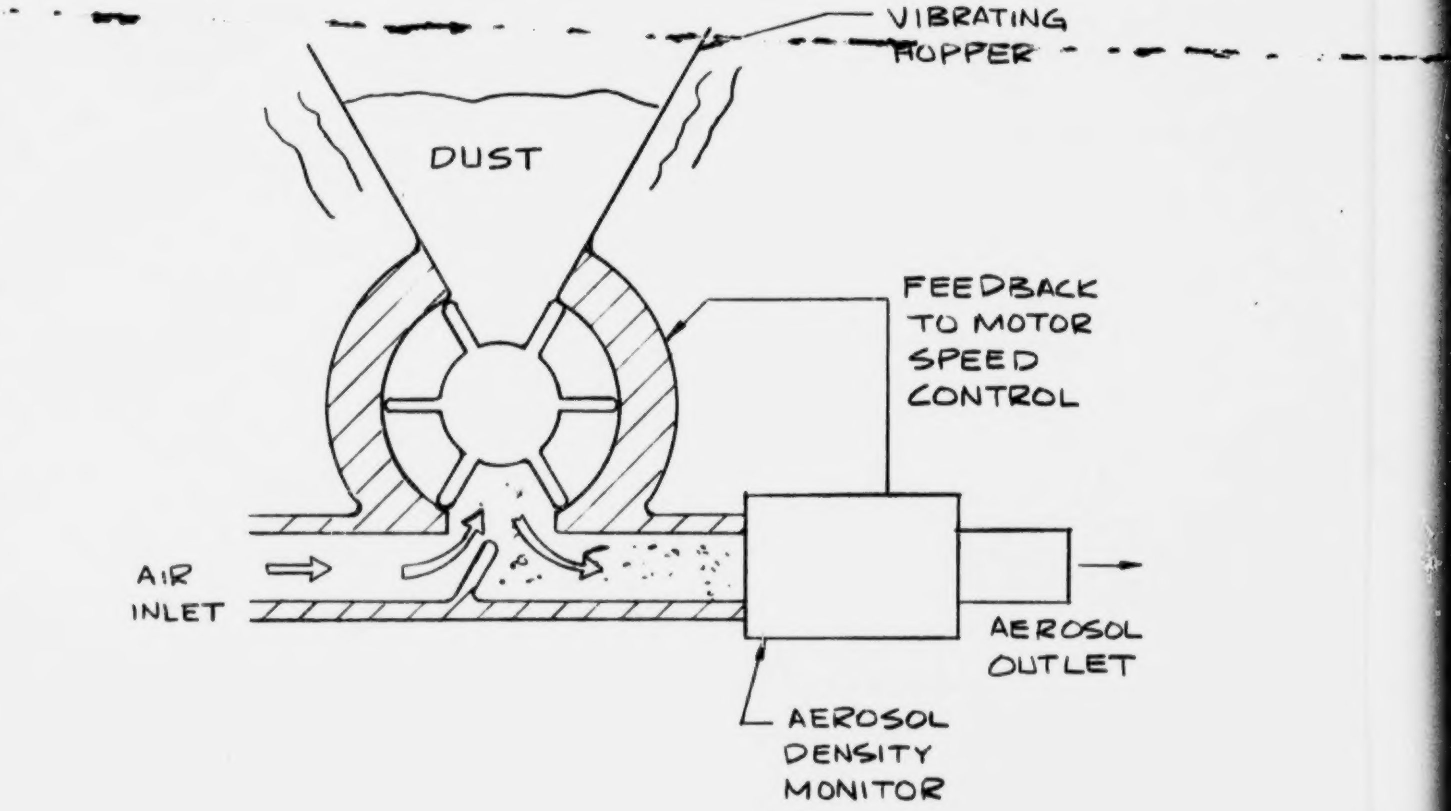

VIBRATING HOPPER
DUST
FEEDBACK TO MOTOR SPEED CONTROL
AIR INLET
AEROSOL OUTLET
AEROSOL DENSITY MONITOR

FIGURE 19. VANED IMPELLER METERING DEVICE

A-3923

Another metering method involves shaking a ribbon of dust onto a belt or disc (Figure 20, 21). Belt feeders for particulate metering sometimes use feedback (Figure 20) where the weight of material on the belt regulates belt speed. With the disc metering device, the scraper position determines the ribbon cross-section and rotational speed regulates the delivery rate.

All of the previously described methods are potentially applicable to the particulate wind tunnel. All require some developmental effort, fabrication of special components, and all make use of purchased standard components. The various methods can be ranked by defining a figure of merit as in Table 3 As indicated by the table, the two methods most practical to pursue at the present time are first, the vibrating hopper with orifice regulation, and second, a screw feeder also with some form of feedback regulator.

One reason why the vibrating hopper and screw feeder rate so high is because they are commercially available with the necessary capacities. For example, the Vibra Screw Corporation manufactures a vibrating hopper (Live Bottom Bin) and screw feeder (Vibra Screw Live Bin Feeder).

The screw feeder has a 3 cubic foot vibrating hopper. For our purposes, this small bin would be fed by the larger 50 cubic foot bin.

The chances are high that the large vibrating bin with regulation will work. If not, the screw feeder can be added. The capacity of the basic screw feeder can be modified by changing screw sizes, as shown in Table 2.

TABLE 2

FEED RATES WITH VARIOUS SCREW SIZES

Screw Size (in)	Pounds per Hour
1/4	0.15/1.5
3/8	0.42/4.2
1/2	0.98/9.8
5/8	2.1/21.0
3/4	4.0/40.0
1	11.4/114.0
1-1/2	35.2/352.0
2	92/920

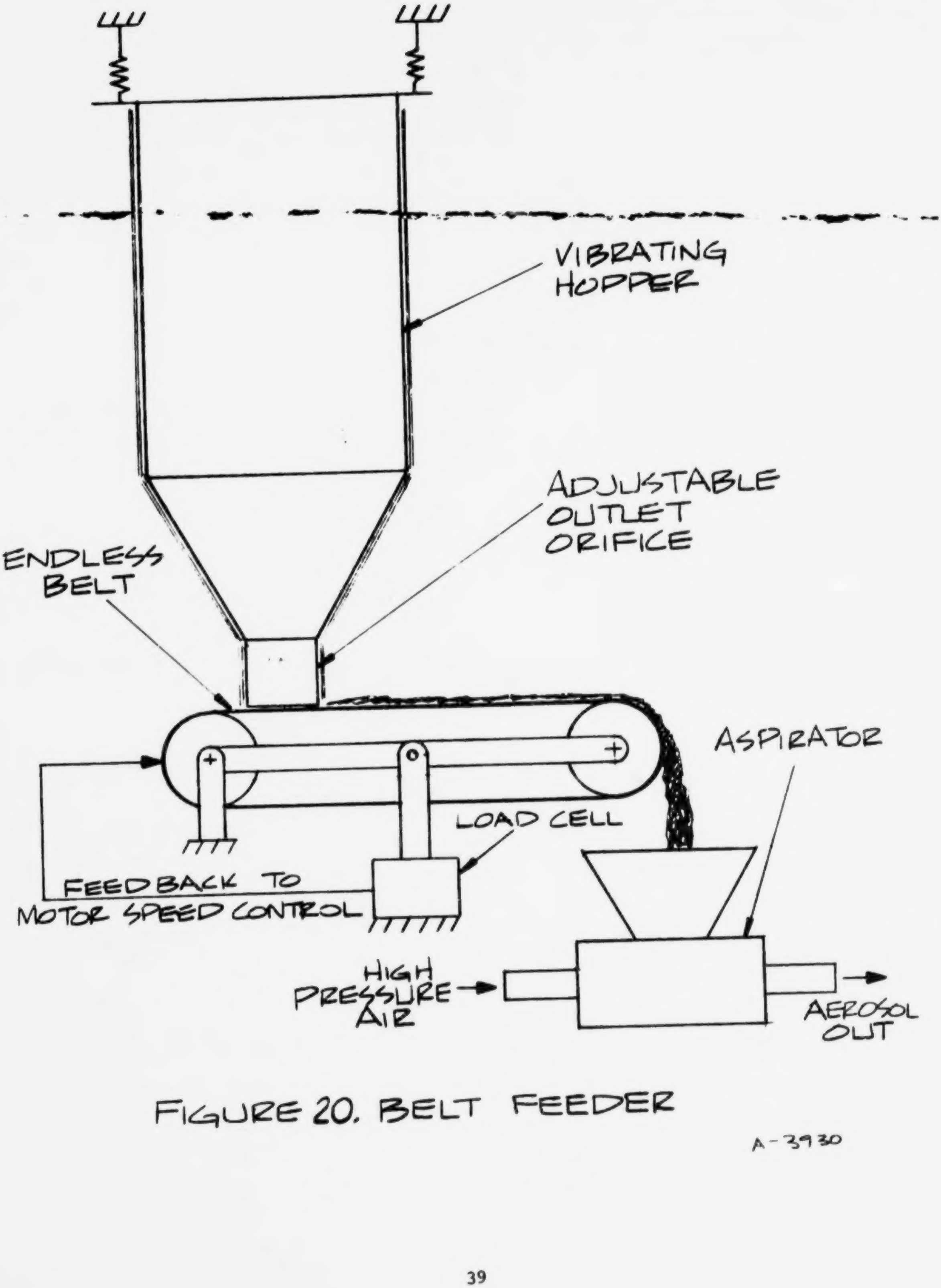
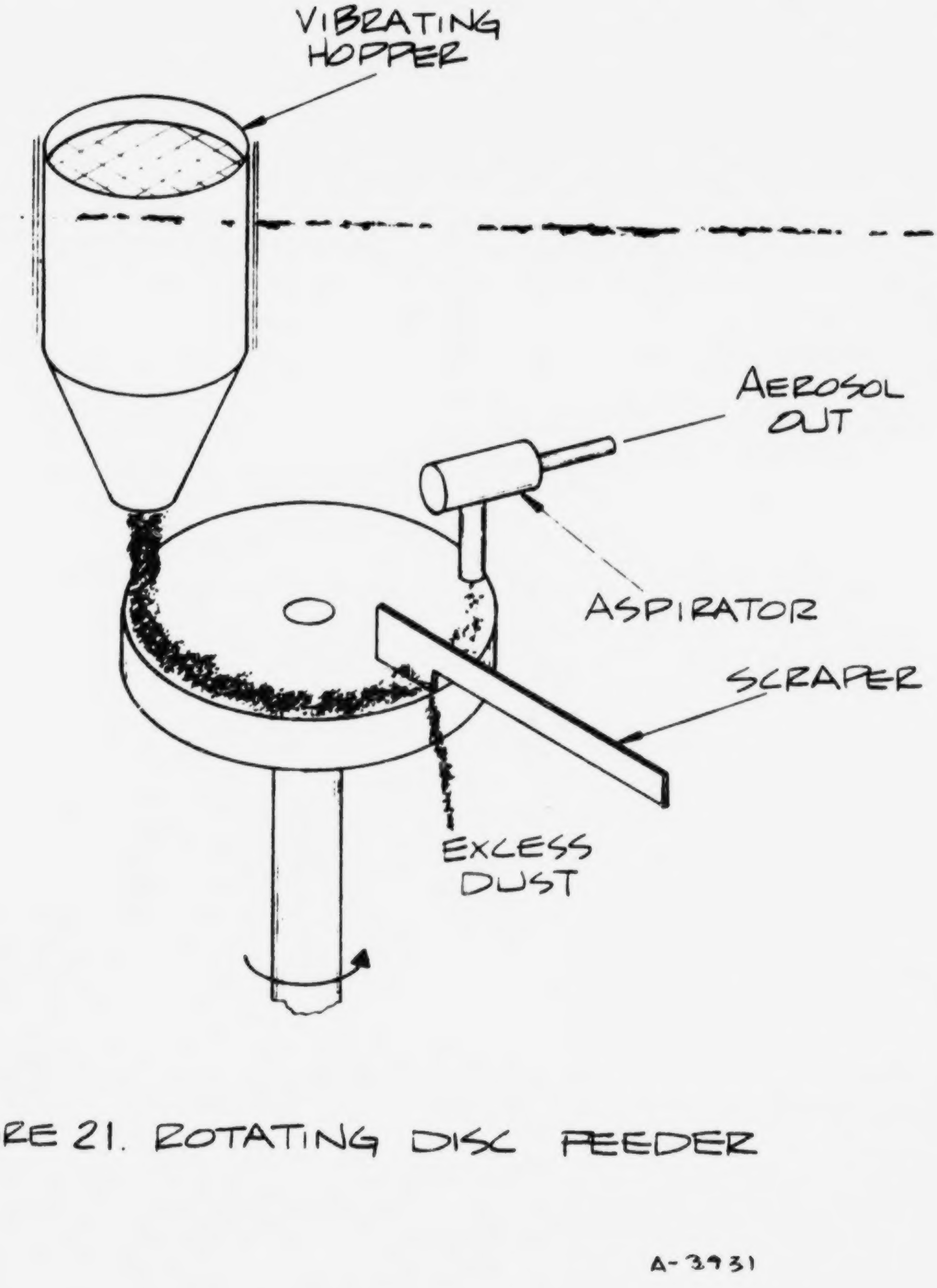

VIBRATING HOPPER
ADJUSTABLE OUTLET ORIFICE
ENDLESS BELT
ASPIRATOR
LOAD CELL
FEEDBACK TO MOTOR SPEED CONTROL
HIGH PRESSURE AIR
AEROSOL OUT

FIGURE 20. BELT FEEDER

A-3930



VIBRATING HOPPER
AEROSOL OUT
ASPIRATOR
SCRAPER
EXCESS DUST

FIGURE 21. ROTATING DISC FEEDER

A-3931

TABLE 3
MERITS OF VARIOUS DUST FEEDING METHODS

Technique	n_1	n_2	n_3	n_4	n_5	N	Rank
	Development Effort	Probability of Success	Flow Constancy	Flow Range	Component Cost	Figure of Merit	
Fluidized Bed	9	0.6	10	5	5	0.7	4
Vibrating Hopper	1	0.9	9	10	1	81.0	1
Screw Feeder	2	0.9	9	10	2	20.3	2
Vaned Impeller	5	0.5	2	3	2	0.3	6
Slotted Discs, Cylinders	10	0.5	5	3	2	0.4	5
Belts, Discs with Scraper	5	0.5	8	3	2	1.2	3

Definitions:

1 Development effort, n_1, rating from 0 to 10 where the lowest numbers represent the least effort

2 Probability of success, n_2, rating from 0 to 1, based on predicability, knowledge of previous successes with similar equipment

3 Flow constancy, n_3, rating from 0 to 10, with smoothest delivery and constancy rated highest.

4 Flow range, n_4, rating from 0 to 10, with highest number representing greatest range capability

5 Component cost, n_5, rating from 0 to 10, rating increases with cost

6 Figure of Merit, N, previously described ratings combined so that

$$N = \frac{n_2 n_3 n_4}{n_1 n_5}$$

The highest possible value for N is 100.

It is therefore clear that the large turn-down ratio necessary in this dust feeder can be attained through screw size change. The manufacturer claims that "minute-to-minute deviations from any given set rate are generally less than 1 or 2 percent - from hopper full to hopper empty." The screw speed control can be manual, electrical or pneumatic, the latter two being adaptable to a closed-loop feed control system.

Using either a vibrating bin alone, or in conjunction with a screw feeder, the metered dust would be transformed into an aerosol by an aspirator (Figure 18) The aerosol would then be divided up into multiple streams for the multi-jet injection system described earlier. Thus, based upon the discussion presented above and discussions with others working in the field with dust feeders, it is recommended that the initial dust feeding system be composed of a simple live bin hopper feeding dust to an aspirator. Initial experiments with this system will indicate whether or not the necessary type of control is possible with a simple slide valve in the bin. If this control is adequate, the operation of the slide valve can be automated with a feedback system. If not, a screw-feeder can be added, with a feedback control system if the combination is successful. This step-by-step, modular approach to the feeder system design is deemed most appropriate at this time, since an experimental program is mandatory before committing to a final design concept.

2.4.5 Test Section Diameter and Length

The basic considerations for selection of a test section diameter and length are:

- What size of models, probes, or instruments will be tested?
- What types of tests will be run?
- What length is necessary for mixing of the dust?
- What interference might be caused by wall boundary layers?

Wall boundary layer thickness can be calculated by standard methods; results for two velocities are shown in Figure 22. The lowest velocities give the thickest boundary layers. Assuming that 20 feet of test section is needed for dust mixing and that a 6-inch diameter low turbulence core flow is desired, the test section must be at least 18 inches in diameter. Consideration of typical probe, instrumentation, and model sizes indicates that a 2-foot diameter would be much more convenient. Also, there is some interest in having the capability to test at a minimum of 10 diameters (upstream or downstream) from any change in flow direction. Therefore, the optimum test section size appears to be a 2-foot diameter section approximately 40 feet in length. This length provides the additional

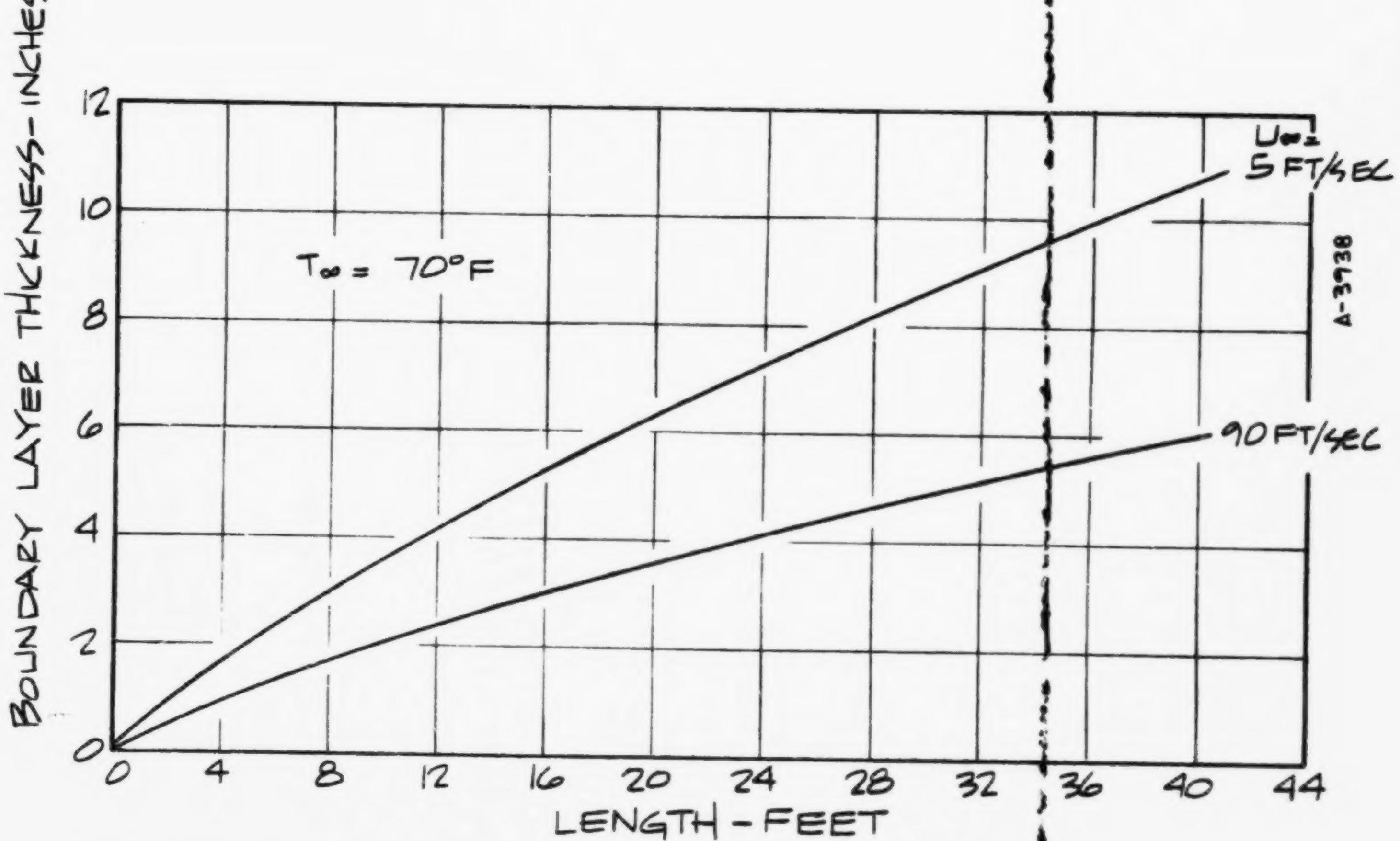


FIGURE 22 BOUNDARY LAYER GROWTH IN THE TEST SECTION

advantage of a thick region of wall boundary layer flow near the downstream end, allowing simultaneous testing in both low and high turbulence flow. Since the required mixing length is unknown, a 40-foot test section is also strongly recommended as a conservative solution to the dust mixing problem.

2.4.6 Test Gas Heating

There are several possible ways to heat the test gas to temperatures up to 450°F. Open circuit operation using direct combustion as an energy source has been eliminated earlier due to complex control and heat exchange problems. With closed circuit operation, other possibilities are illustrated schematically in Figure 23. These systems include

- Direct gas-to-gas heat exchanger
- Indirect, condensate-to-gas heat exchanger
- Electric resistance heater
- Burner source with bypass and bleed system

The advantages and disadvantages of each of these systems are described in Table 4. Based on information presented in this table and experience with similar systems at Aerotherm, either the indirect heat exchanger or the resistance heater appears to be a possible solution for this test facility design. Cost and availability of these systems indicate, however, that the electric resistance heater is the most logical choice.

A second consideration in the heater selection is that a re-heater will be needed for cold (air-conditioned) operation as well. The heater control should allow precise operation at low power settings for use in an air-conditioner capacity.

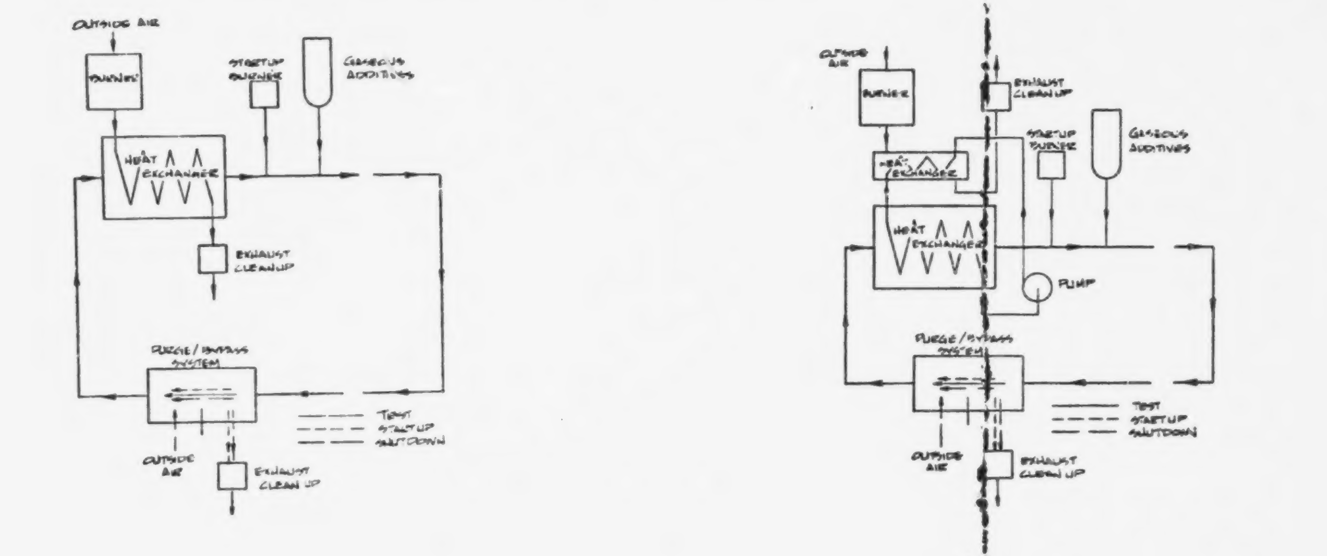
2.4.7 Air Conditioning

A brief study of the merits of running the cold flow tests open circuit has indicated that there is little, if any, advantage in this approach. Large savings in the complexity, size, and cost of the air conditioning system can be realized with closed circuit air flow. Since hot flow testing requires the closed circuit ductwork, no additional construction is required. Therefore, the cold flow testing should be carried out in a closed circuit mode as well.

The desired conditions in the test gas during cold flow operation are

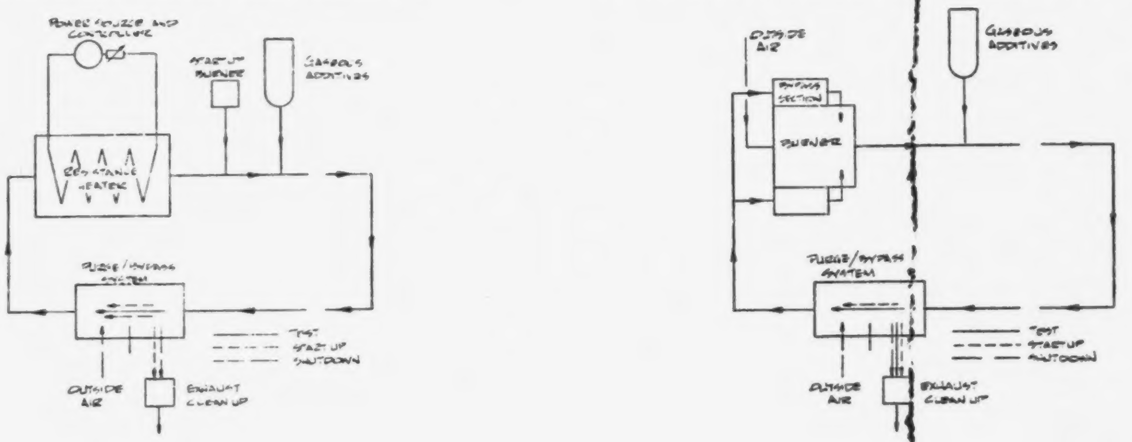
temperature: 70°-100°F

relative humidity: 10-80%


OUTSIDE AIR
BURNER
HEAT EXCHANGER
STARTUP BURNER
GASEOUS ADDITIVES
EXHAUST CLEANUP
PURGE/BYPASS SYSTEM
OUTSIDE AIR
EXHAUST CLEAN UP
TEST
STARTUP
SHUTDOWN
PUMP

a) Direct Gas-to-Gas Heat Exchange

b) Indirect, Condensate-to-Gas Heat Exchanger


POWER SOURCE AND CONTROLLER
RESISTANCE HEATER
STARTUP BURNER
GASEOUS ADDITIVES
PURGE/BYPASS SYSTEM
OUTSIDE AIR
EXHAUST CLEAN UP
TEST
STARTUP
SHUTDOWN
BYPASS SECTION
BURNER

c) Electrical Heating

d) Burner with Bypass and Bleed

Figure 23. Closed Circuit Test Gas Heating Methods

TABLE 4

HEATER OPTIONS

Configurations	Advantages	Disadvantages
Direct, gas-to-gas heat exchanger	No secondary working fluid required. Economical to operate. Low maintenance. Commercially available.	Excessive heat transfer surface material temperature or large amount of transfer surface required. Large, expensive secondary system hardware necessary to supply hot gas side. Difficult to control
Indirect, condensation to gas heat exchanger	Compact exchanger design. Large transfer rates. Commercially available. Good control characteristics over limited temperature range.	Two expensive secondary systems (liquid and burner) required to supply hot side. Secondary fluid useful over limited temperature range. Secondary fluids other than water may be expensive.
Electrical resistance heater	Minimum accessory equipment required. Good control characteristics. High temperatures possible. Comercially available. Little or no maintenance.	Electrical insulation required. Expensive control equipment necessary at higher power.
Burner source with bypass and bleed system for energy makeup	Small amount of secondary system hardware required. Low pressure drop through heater section. Wide temperature range possible. Low maintenance.	Parallel stream mixing required to obtain correct bulk temperature. Difficult control. Not commercially available - development necessary.

Any combination of temperature and humidity in this range should be attainable. The large range of conditions is seen more clearly on a psychrometric chart, as shown in Figure 24. The conditioning system must provide dew points as low as 15°F and as high as 92°F. In addition, the air conditioning system must be designed for both startup or change in set-point operation, and steady state operation. During startup or change in set-point, heating or cooling and humidification or dehumidification may be required depending on the initial gas condition. During steady state operation, temperature conditioning will be primarily cooling, since viscous dissipation of the test gas kinetic energy is expected to result in a steady state temperature of 150°-200°F at high speeds. A very small amount of humidification will also be needed, as explained below.

A typical air conditioning system for this application is illustrated schematically in Figure 25. Humidification and heating are accomplished rather simply with steam nozzles and a small electric heater, respectively. The problems arise in the cooling coil and dehumidifying system. Cooling is most commonly accomplished in either of two ways:

1. Direct expansion refrigeration - A liquid refrigerant is expanded or throttled to a low temperature and is passed through the cooling coils. Energy transferred from the warmer test gas evaporates the refrigerant. It is then compressed, condensed, and is ready to circulate again through the cooling coils. Numerous refrigerants are available, and the selection is based primarily on the temperature desired in the refrigerated zone.

2. Indirect refrigeration - In larger systems having many cooling coils, it is often most convenient to have a central vapor-compression or other type of refrigeration system which cools water, ammonia, or a low temperature brine at a central location. The chilled water or brine is then circulated to the various cooling coils.

The second of these two options is obviously least expensive if chilled water is already available from a central source. In the Durham Research Facility, there is a central absorption-type water chiller located in a room adjacent to that which will house the wind tunnel. Therefore, the suitability of utilizing this chilled water has been examined.

The first consideration in using chilled water is that its temperature is approximately 45°F. Thus, as the test stream passes over the coils, air immediately adjacent to the coils will attain a temperature of approximately 50°F. This, then, is the lowest dew point temperature that can be provided by chilled water alone. If all the water (from the air stream) that collects on the coils at 50°F is separated from the flow, and the air is heated back to 70°F the relative humidity would be approximately 50 percent. This is far from the

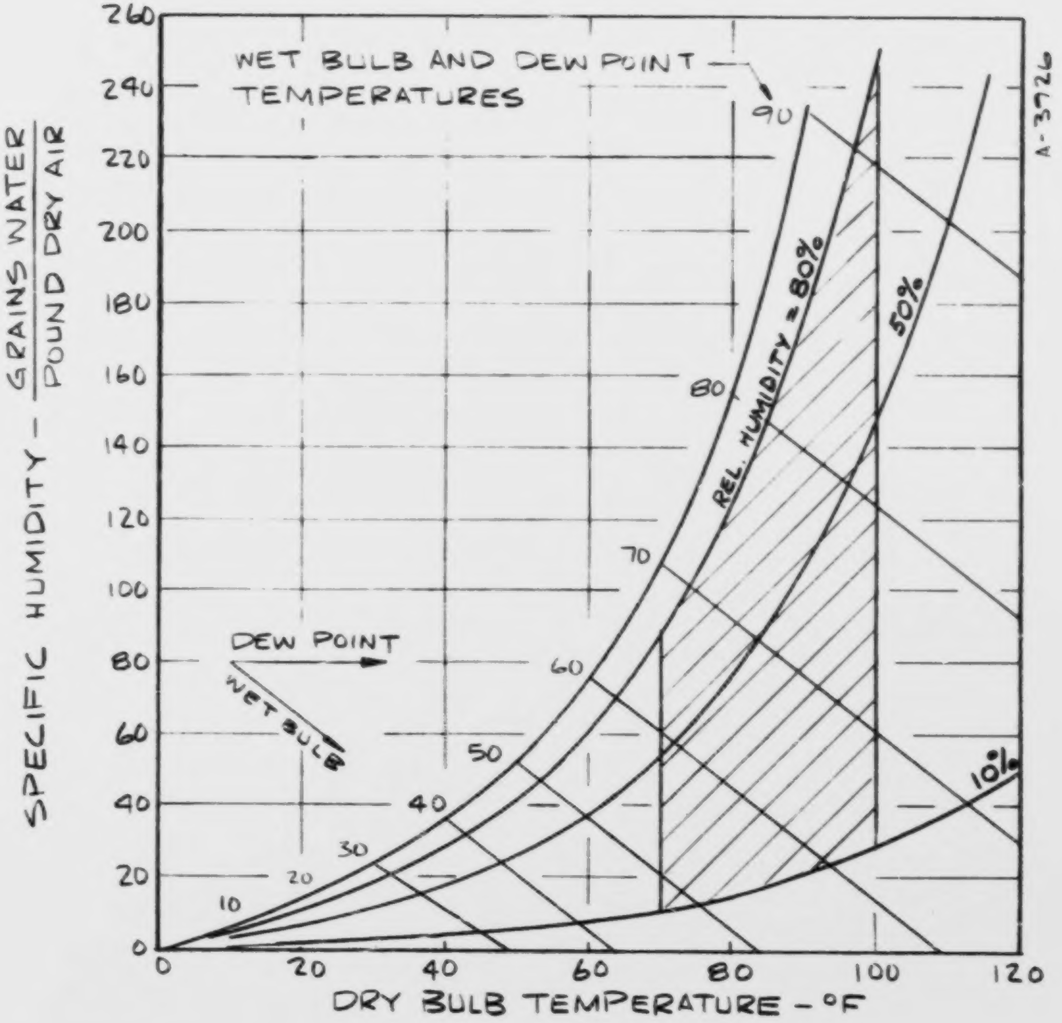


FIGURE 24. PSYCHROMETRIC CHART

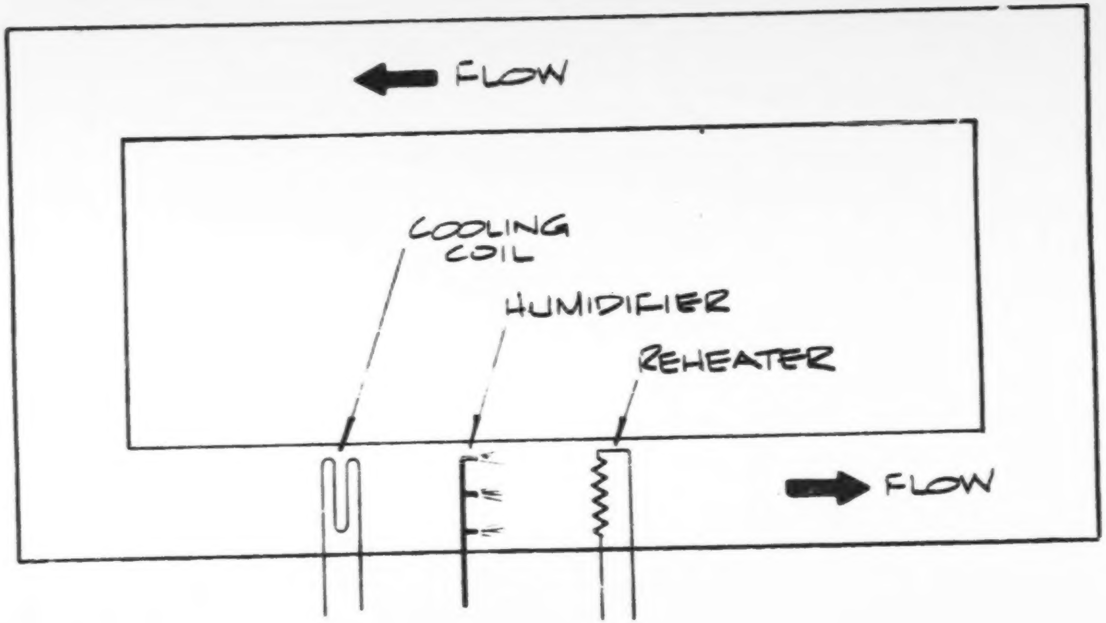

FLOW
COOLING COIL
HUMIDIFIER
REHEATER
FLOW

FIGURE 25. TYPICAL AIR CONDITIONING SYSTEM.

desired low of 10 percent. Further dehumidification would require that water be removed from the air by some other means. One way to accomplish this is with a rotating drum, adsorbent dehumidifier, shown schematically in Figure 26. The rotating drum dehumidifier complicates the conditioning system significantly since it requires a separate scavenging air supply, heating device, and complex controls. In addition, the unit can easily be fouled by dust in the gas flow, and is expensive. A typical dehumidifier cost would be $10,000 for the size required in this installation, and this cost does not include any controls or installation. Other dehumidifiers are equally expensive and complex. Thus, the use of chilled water from a central source does not seem to be an economical choice if the entire temperature and humidity range must be attained.

The use of direct expansion refrigeration with ammonia or freon allows lower temperatures on the coils. Assuming an average temperature of 35°F on the coil and referring to Figure 24, it is seen that a relative humidity of 28 percent can be achieved at 70°F. Lower average coil temperatures result in ice formation on the coils, which must be removed periodically with a defrost cycle. This defrost cycle would result in a fluctuating test gas temperature and humidity level unless the run times were held to less than 1 hour, or unless parallel cooling systems were designed to run in an alternating mode. The 1 hour run time is considered to be too short, while the parallel systems approach is complex and expensive. Thus, a direct expansion refrigeration system offers only a small relative humidity advantage over the chilled water approach, and also needs a dehumidifier to attain the desired 10 percent relative humidity. Other problems with the direct expansion system arise when it is exposed to the 450°F flow during a hot run:

- This temperature is higher than the critical temperature of the refrigerant, resulting in unacceptably high pressures in the coils.
- This temperature may result in "baking" of oil films on the coolant coil interior passages.

Thus, the direct expansion refrigeration approach is not a good choice for this wind tunnel.

Based upon these considerations, the chilled water approach is recommended for the initial construction phase of this facility. At a later date, if the 10 percent relative humidity value is still desired, the chilled water coils can be used in conjunction with a dehumidifier to attain this value. With the chilled water alone, the relative humidity values listed in Table 5 below will be attained:

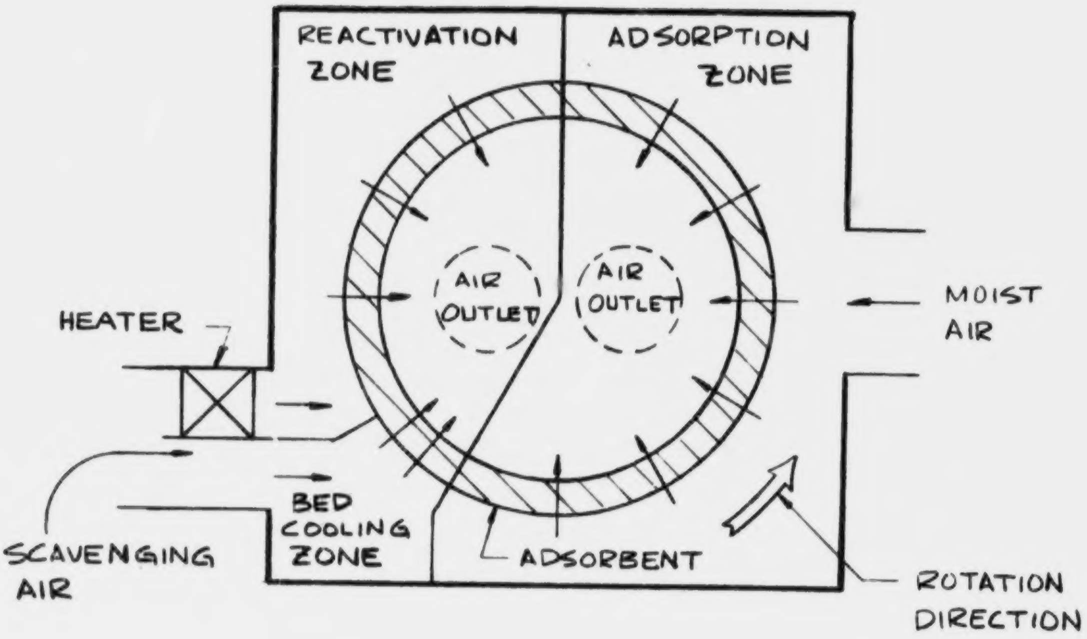

REACTIVATION ZONE
ADSORPTION ZONE
AIR OUTLET
AIR OUTLET
HEATER
MOIST AIR
BED COOLING ZONE
SCAVENGING AIR
ADSORBENT
ROTATION DIRECTION

FIGURE 26. ROTATING DRUM ADSORBENT DEHUMIDIFIER

A-3925

TABLE 5

RELATIVE HUMIDITY VALUES WITH A CHILLED WATER SYSTEM

Air Temperature °F	Relative Humidity %
70	50
80	35
90	26
100	18

2.4.8 Charging the Tunnel with Combustion Products

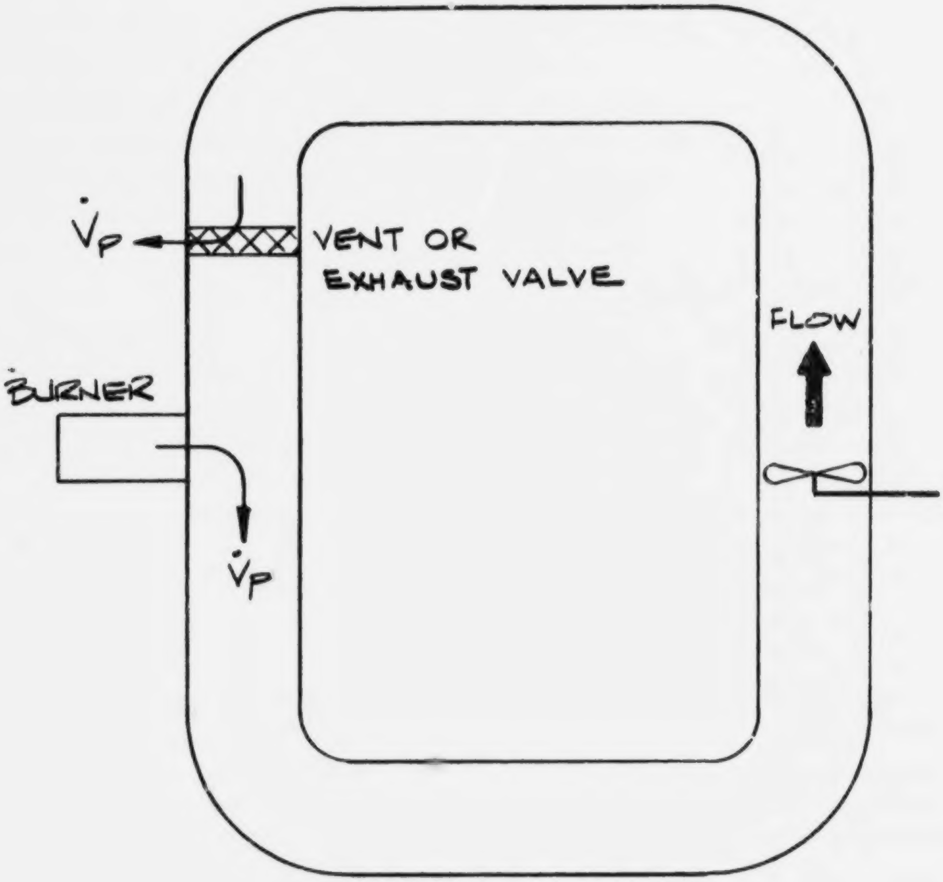
In many cases it will be desirable to employ as a test gas actual combustion products: a realistic mix of N_2, CO_2, and H_2O. Such a test gas could be obtained either from bottled gases, appropriately mixed and injected, or from an actual combustion source. Furthermore, this test gas could be obtained either in full-flow amounts, or in much smaller amounts used to pre-charge the tunnel before test operations begin.

Brief study shows that full-flow systems are not attractive in either supply system. For bottled gases, an inconvenient number of bottles would be required, and for a full-flow combustion system, the furnace would be a sizeable one, roughly equivalent to a 3000 kw generating facility. Consequently, a pre-charge system is strongly preferred.

Figure 27 illustrates how the pre-charge system would function. At the start the tunnel is filled with air. Tunnel circulation is established, the air is heated to avoid condensation, and the combusiton unit exit valve is opened. The burner is started, feeding combustion products into the tunnel. The vent system withdraws a like amount. In 1 to 2 hours, the tunnel becomes charged with >99 percent combustion products. The burner may then be shut down and the burner exit valve closed. Fine tuning of the exhaust product gas composition may be accomplished by the introduction of bottled gas, if desired. The pre-charged tunnel is then ready for testing.

To fill the tunnel in 1 to 2 hours will require a combustion product addition at some 10% of the tunnel volume flow rate. A simple analysis based upon the schematic diagram of Figure 27 and the assumption that there are only small pressure changes around the circuit results in the expression

$$x_c = 1 - e^{\frac{\dot{V}_p \theta}{V_t}}$$



$\dot{V}_P$
VENT OR EXHAUST VALVE
FLOW
BURNER
$\dot{V}_P$

FIGURE 27. TUNNEL OPERATION DURING COMBUSTION GAS PRE-CHARGE PERIOD

where

X_c = mol fraction of combustion products in the tunnel

$\dot{V}_p$ = volumetric flow rate of combustion products into the tunnel

V_t = tunnel volume

θ = time from initiation of filling

Figure 28 shows the required tunnel fill time with the combustion product fill rate as a parameter. This analysis confirms that a 400-500 scfm burner is adequate. This corresponds to about 2,000,000 Btu/hr, or 15 gal/hr of fuel oil or 3000 scfh of natural gas

b. Combustion Products Burner

As discussed above, it is not feasible to supply combustion products in a continuous flow equal to the test flow. Instead, a relatively small burner will be used to "charge" the tunnel over a period of time with combustion product test gas. A burner of approximately 2,000,000 Btu/hr capacity will result in an acceptable charging time. A burner of this small size could physically be located in the tunnel as a duct burner; however, such a burner would experience unacceptably poor combustion conditions as the tunnel became charged with combustion products. Therefore, the burner must be located to the side of the tunnel, mounted in a customary refractory combustion chamber or firebox. Great care must be taken to optimize the burner selection and firebox design to produce combustion products as near as possible to those produced by the larger combustion units being simulated in the tunnel experimentation programs. These larger burners operate relatively close to stoichiometric conditions (nominally 10% to 20% excess air); most small burners of the type considered here run well only with more than 50 percent excess air. For flexibility in test operations, the burner should also be a dual-fuel unit capable of running either on light distillate fuel oil or on natural gas.

c. Injection of the Combustion Products into the Tunnel

Additional difficulties arise when one attempts to inject the hot combustion products into the tunnel. The temperature of the combustion products is expected to be approximately 2800°F as they leave the combustion chamber.*
Wind tunnel internal surfaces cannot be allowed to reach these high temperatures, therefore some action must be taken to prevent this occurrence. Possible alternatives are

---

*A submerged combustion unit could give a lower temperature exhaust, however its price is unacceptably high.

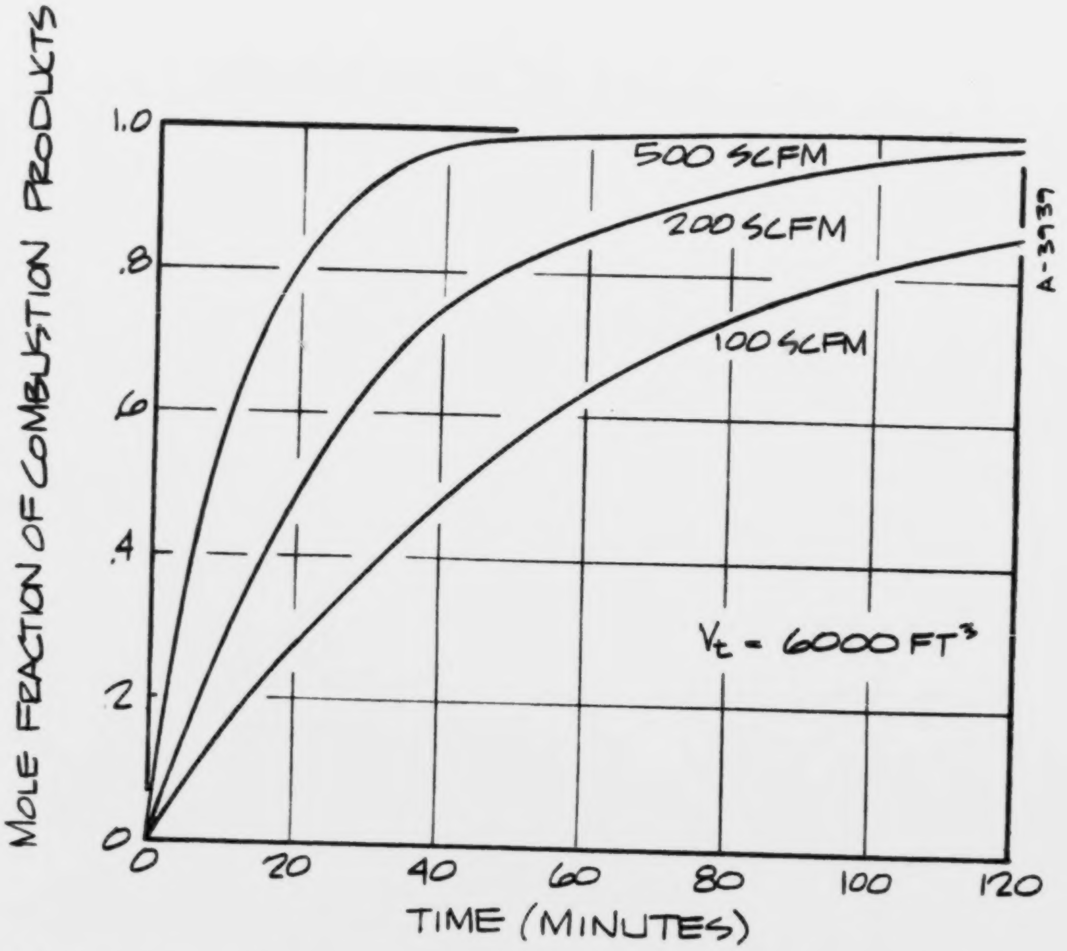


FIGURE 28. MOLE FRACTION OF COMBUSTION PRODUCTS IN TUNNEL GAS AS A FUNCTION OF TIME FOR VARIOUS BURNER PRODUCTS FLOW RATES

1. Transfer energy to another fluid, such as water, in a heat exchanger before injecting the gas
2. Protect the internal surfaces of the tunnel from the hot gases with a refractory material until the point where sufficient mixing with the main flow has taken place
3. Same as above, but water-cool the tunnel surfaces
4. Inject the combustion products such that they do not come into contact with the tunnel walls until sufficient mixing has occurred.
5. Dilute the combustion products with sufficient tunnel air such that injection temperatures are acceptable.

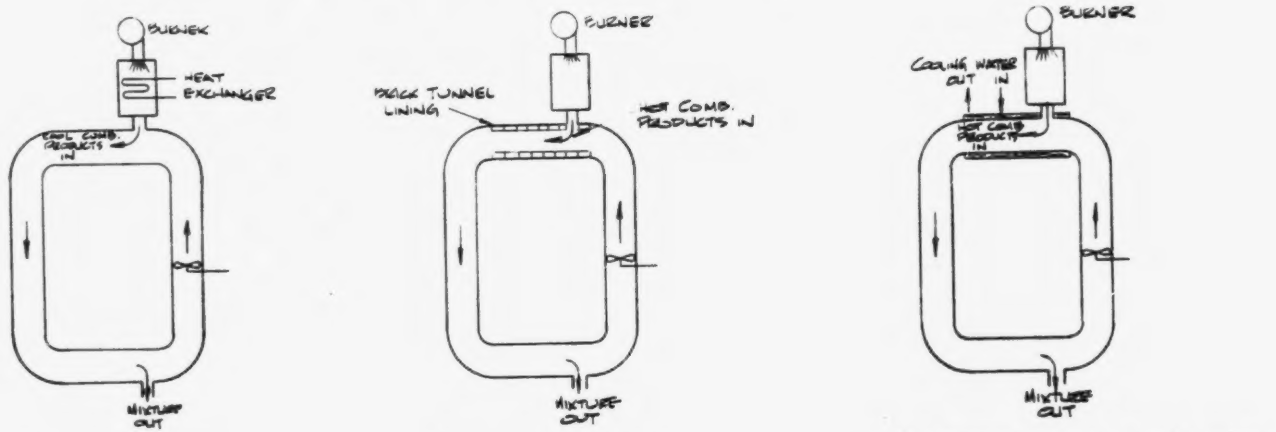
These alternatives are illustrated schematically in Figure 29. Alternative 1, the heat exchanger approach, might involve a small packaged steam boiler with integral burner. Since hardware costs for an appropriately sized boiler may run $6000-$8000, and since installation and maintenance would also be expensive, other alternatives have been examined. Alternative 2, refractory duct lining, would result in a poor aerodynamic surface, a very heavy duct, and difficult cleaning problems. The refractory would probably generate undesirable dust particles, which may interfere with testing, depending on the injection location. Alternative 3 requires expensive duct fabrication, and expensive auxiliary hardware to pump the water. Alternative 4 is the least expensive but is risky. Forty to eighty jet diameters are needed to bring the jet centerline temperature down to 400°F. Thus, unless the jet were very small (~3 inches), running length for this approach is not available. An obstruction in the flow circuit is also undesirable. Alternative 5 requires additional ductwork and an extended combustion chamber, but these modifications are relatively low in cost. Control is easy, and the air conditioning heat exchanger can be used to keep tunnel temperature down if this becomes a problem. Therefore alternative 5, employing tunnel bypass gas as a diluent, is recommended as the most practical injection method.

2.4.9 Fan, Motor, and Speed Control

The considerations in selecting a fan and the motor that drives it are discussed here. Also discussed are various methods of achieving speed control over the desired range.

a. Fan or Blower

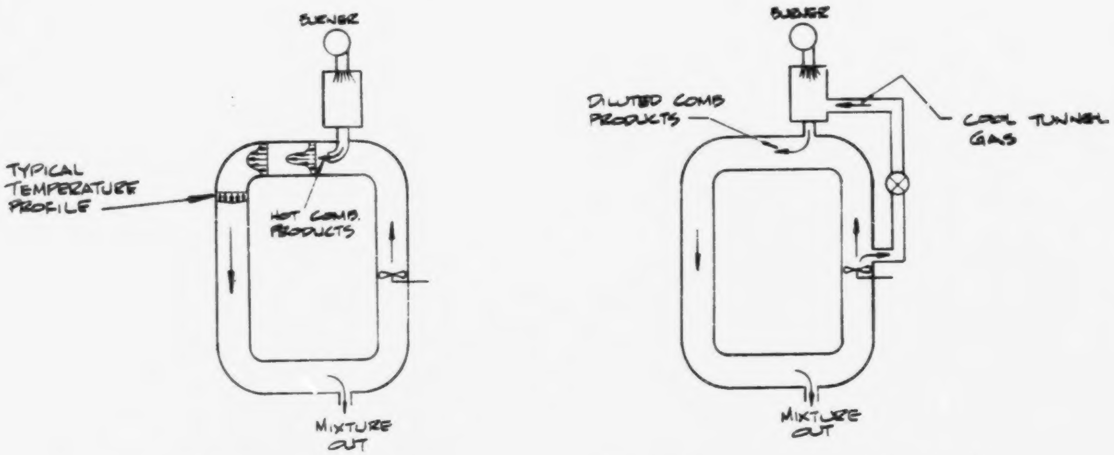
Most large, closed circuit tunnels used for aerodynamic studies have a specially-designed, low speed axial fan (or fans) located downstream of the


BURNER
HEAT EXCHANGER
COOL COMB. PRODUCTS IN
MIXTURE OUT
BURNER
BRICK TUNNEL LINING
HOT COMB. PRODUCTS IN
MIXTURE OUT
BURNER
COOLING WATER OUT IN
HOT COMB PRODUCTS IN
MIXTURE OUT

1) HEAT EXCHANGER

2) REFACTORY LINING

3) ACTIVELY COOLED TUNNEL WALL


BURNER
TYPICAL TEMPERATURE PROFILE
HOT COMB. PRODUCTS
MIXTURE OUT
BURNER
DILUTED COMB PRODUCTS
COOL TUNNEL GAS
MIXTURE OUT

4) CAREFUL INJECTION

5) DILUTION BEFORE INJECTION

FIGURE 29 COMBUSTION PRODUCTS INJECTION TECHNIQUES

test section, somewhere in the diffuser portion of the return circuit. This approach is not appropriate for this tunnel, however, for the following reasons:

- The fan would be exposed to heavy particulate loadings
- Axial fans cannot generally supply the large pressure rise which will be needed to accommodate a baghouse in the flow circuit.

The first objection can be overcome by placing the fan upstream of the test section, and upstream of the particle injection apparatus. The second objection can be resolved by using a centrifugal blower. The centrifugal blower located upstream of the test section in both open and closed circuit wind tunnels has just recently gained acceptance in the wind tunnel design community.[21] The reason for this is the commercial availability of airfoil-type blades in centrifugal blowers. The conventional, radial-vane type of blower used in many industrial applications was generally judged not suitable for wind tunnel work due to its high noise level and pulsating flow characteristic. With the advent of airfoil blades, the centrifugal fan offers numerous advantages compared to the axial fan, which include

- Higher pressure rise
- Wider speed range with good flow quality
- Comparable or lower noise level
- Low swirl at the fan exit.

Thus, an airfoil-blade, centrifugal fan is incorporated into this tunnel design.

b. Motor and Speed Control

Selection of a drive motor for the wind tunnel must involve consideration of how the tunnel speed will be controlled. Since an 18:1 turn-down ratio is required for this tunnel, use of dampers or a bypass system with a constant speed fan will not provide the type of control needed. Additionally, the use of gasoline engines, steam or gas turbines, and most other novel propulsion schemes can be rejected on the basis of first cost, reliability, complexity of control, or any combination of these and other reasons. Thus, the question of motor selection and speed control quickly boils down to what type of electric motor and speed controller should be used. Table 6 summarizes some of the more popular speed control methods which have been used in wind tunnels. For the wide range of conditions of interest in this tunnel, the eddy current coupling to a constant speed a.c. motor has been selected. This system offers a wide control range, low cost, and is simple to use.

TABLE 6

TYPES OF WIND TUNNEL FAN SPEED CONTROL

Primary Motor	Secondary Unit	Other Units	Speed Control	Advantages	Disadvantages
Const. speed a.c. motor	d.c. generator	d.c. motor coupled to fan	Output of d.c. generator controlled by field current. Controls d.c. motor speed directly	High efficiency, excellent control	High initial cost. Occupies large amount of space
Const. speed a.c. motor	---	---	Change pulley size	Low cost	Narrow range of speeds possible. Cumbersome to change tunnel speeds
Const. speed a.c. motor	---	Eddy current clutch coupled to fan	Clutch excitation controls torque transmitted. Fan speed adjusts to torque setting	Wide variation in speed possible. Infinite number of set points. Low cost	Low efficiency at low speeds
Shunt wound d.c. motor	---	---	Resistance in series with armature	Low cost	Large power losses at low speed. Speed varies widely with load making control difficult
Shunt wound d.c. motor	---	---	Shunt field rheostat	Simple, reliable	Maximum turn down ratio is 4 or 5 to 1. Controlling large amount of power

2.4.10 Materials of Construction

All types of materials are used for wind tunnel construction, including wood, metal, concrete, plaster, plastics, and combinations of these. The great majority of subsonic tunnels, which are in universities or small research laboratories, are constructed of wood with use of some sheet metal fairings. In addition to being inexpensive and easy to work with, wood offers a good vibration damping capability. In the present tunnel design, with operation at test section temperatures of 450°F, wood is inappropriate as a construction material, as are most others mentioned above. Therefore a steel tunnel appears to be in order, and the discussion of materials of construction boils down to selecting the type of steel - mild or stainless.

The use of stainless steel as a construction material is a straightforward but expensive solution to the problem of preventing exposed surface corrosion, rust formation, and undesirable particulate material in the test gas. Raw material costs for stainless steel components are roughly five times higher than mild steel, with fabrication costs (welding, cutting, grinding) slightly higher as well. Alternatives are the use of high temperature protective coatings, or possibly using unprotected mild steel in noncritical areas. In the recommended tunnel design, all of these solutions are used in various sections of the tunnel. The particular materials are discussed in Section 3 along with the details of the tunnel design.

SECTION 3

FACILITY DESIGN

A general description of the entire facility is given, then each major component is discussed in detail. Controls and instrumentation details are presented in Subsection 3.3 and utilities requirements are outlined in 3.4. Support equipment and other details are discussed in 3.5.

Under the present contract, a complete description of the tunnel design along with "mechanical outline" drawings of the major tunnel components were called for. Also, utility and control circuit layouts were required. It was found, however, that it was not possible to arrive at satisfactory descriptions of these major tunnel componets without fixing many of the design details. Therefore, in addition to mechanical outline drawings, several detail drawings have been included in this report. These drawings are included at the back of this report in the Appendix, and are labeled with drawing numbers beginning with the letter "M", (e.g., M-1). While these drawings do contain many design details, they should not be construed as a complete set of final detail drawings. Other drawings of a schematic nature are included in the text with ordinary figure numbers.

GENERAL FACILITY DESCRIPTION

Layout and elevation drawings of the facility are included as drawings M-1 and M-2. These drawings indicate the placement of the tunnel in the Durham facility, give basic dimensions, and label the various pieces of equipment. The test gas enters the airfoil-type centrifugal fan at the center and exits horizontally through a 28" x 22" rectangular duct at velocities up to 66 feet per second. The fan forms one of the corners of the flow circuit. The flow is immediately diffused in a simple, straight-walled diffuser to decrease its velocity. The straight-walled diffuser design was selected since flow quality at this point is not critical. The diffuser ends in a 6'0" by 6'0" duct with a honeycomb provided at the intersection to break up any eddies or swirl originating in the fan or diffuser. Maximum velocities in this duct are 8 feet per second. The flow then passes through a shutter-type valve and along the 6'0" duct to the gas conditioning section. There, it encounters aluminum-finned cooling coils, steam distribution manifolds, and resistance heater elements. The gas conditioning section of the duct is removable for modification, cleaning, and maintenance. Control of the gas cooling, heating, and humidification equipment is completely automatic.

Gas flows out of the gas conditioning section and into the first corner. Turning vanes are included at this corner to prevent large separation and recirculation zones. A square to round transition section follows, routing the flow into a round (cross-section) plenum or settling chamber. This plenum includes two screens and one honeycomb whose purpose is to reduce the turbulence level in the tunnel. The honeycomb-screen frame is removable to allow cleaning, access to the contraction, and modification. Dust is injected isokinetically into the flow just downstream of the screens through seven nozzles arranged in a symmetric pattern. The dust-laden flow then accelerates through the 9:1 contraction section and into the test section.

The test section is a 2-foot diameter, 40-foot long duct. It is composed of three 10-foot sections and two 5-foot sections. These sections are mounted on rollers, are readily detachable, and can be arranged in many configurations. The 5-foot sections contain four windows each and are intended to hold the model, probe, or test device. The 10-foot sections contain two windows each. Installation and access to the test fixture is accomplished by removing the Marman clamps which hold the sections together, rolling one or more sections out of the way, and reaching in through the ends. Access may also be gained through the window openings.

Flow out of the test section proceeds into the return circuit elbow. A large mesh screen at the entrance to this elbow catches any objects which may have broken loose in the high speed test section flow. A vent downstream of the screen allows the tunnel to adjust the amount of mass flowing as the temperature changes and controls the test section pressure. Turning vanes are included in both corners of the elbow and flexible duct sections allow for thermal expansion and contraction of the entire test section length. Flow out of the elbow moves into the conical diffuser section, where its velocity is reduced from a maximum of 90 ft/sec to a maximum of 10 ft/sec. The diffuser is mounted above the test section to save floor space. The low speed flow out of the diffuser then passes into a rectangular duct which leads into the baghouse.

The baghouse is fully automatic, self-cleaning model with high temperature bags. The entrance and exit to the baghouse have been modified to accommodate the large cross-sectional area ductwork which is appropriate for a wind tunnel circuit. Flow out of the baghouse moves through a large rectangular duct back to the fan inlet.

The tunnel also incorporates inlet and exhaust ducts, leading from the top of the 6'0" by 6'0" duct just downstream of the fan, which are used to purge the system after a test run. The exhaust duct is also opened when the tunnel is being filled with exhaust products. The burner and firebox are located on the floor behind the test section. Dilution of combustion products from the burner is accomplished by routing some of the test gas from the main blower into the firebox downstream of the flame zone while the burner is in operation. Thus, filling the tunnel with combustion products is accomplished by injecting all the products of combustion from a burner into the tunnel, and rejecting an equal portion of the mixed test gas to the atmosphere through the exhaust duct. Once the tunnel is filled with combustion products, the burner is shut off.

Materials of construction were discussed in a general sense earlier in this report. Referring to drawings M-1 and M-2, materials can now be discussed in more detail.

The factors considered in deciding which type of steel to use were

- Environment
- System requirements
- Costs of material, fabrication, and maintenance
- Durability

Going around the wind tunnel circuit,the material choices with explanations are as follows:

- Blower - handles high temperature gas of possibly corrosive nature, difficult to refurbish protective coatings for maintenance. Loosened rust or coating particles could affect tunnel test. A stainless steel alloy, e.g., 300 series, is recommended for this component.
- Blower-to-Gas Condition Section - Rusting is possible, however area is accessible for maintenance. Stainless steel (300 series) is preferable, however mild steel may be used for economy in construction. This section weighs about 1000 pounds so the cost in stainless would be about $2000 more than for mild steel. The maintenance cost if the section were of mild steel would be about equivalent to the cost of the stainless steel. To illustrate, assume 40 hours per year for 5 years at $8/hour. The maintenance cost would be $1600. Therefore stainless steel is recommended.
- Gas Conditioning Section - Very high temperatures in this area from heaters or condensing water from refrigerator, so corrosion potential is most severe in this location. Stainless steel should be used. The amount of material involved is so little that it is not a cost issue.
- Turning Section - Readily accessible for maintenance, heavy assembly weighing about 1200 pounds. Should be of stainless steel (300

series) to eliminate chances of rust or coating particles loosening into flow. Initial economy possible by using mild steel, but cost of stainless steel is probably equivalent to the maintenance cost of a mild steel assembly over a 5 year period.

- Stilling and Converging Sections - Highly detailed components, fabrication cost likely to be substantially greater than material cost. Should be of stainless steel.
- Test Sections - Smooth interior surfaces required, 2-foot diameter of test section virtually inaccessible for application or maintenance of coatings. Stainless steel should be used.
- Double Elbow - Highly detailed area so that fabrication cost dominates. Use stainless steel.
- Diffuser and Inlet Duct to Baghouse - Large bearing structures, some corrosion tolerable since particles loosened go to baghouse. Readily accessible for maintenance. Stainless steel desirable, but mild steel is recommended for economy.
- Baghouse - Difficult to maintain interior because of dust. Rusting is almost certain to occur at the anticipated elevated temperatures using mild steel and a protective coating. The worst consequence of rusting is eventual penetration of the thin (14 gage) sheet metal which the baghouse is constructed from. Rust particles could also effect measurements in test section. One construction of the baghouse could utilize mild steel on the inlet side and stainless steel parts on the outlet side. This would result in some savings. The cost of the baghouse would be about $17,000 in mild steel, $28,000 in stainless steel, and $25,000 with mild steel on the inlet side, stainless steel on the outlet side. This latter combination is recommended.
- Duct, Baghouse to Blower - Inaccessible interior for maintenance of protective coatings, rust detrimental to functioning of tunnel. Stainless steel should be used.
- Support Members - All supports for the ducting can be of mild steel. The environment is that of the laboratory, all members are accessible. Paint used for appearance and rust prevention.

3.2 DETAILED DESCRIPTION OF MAJOR COMPONENTS

Each of the major components of the test facility is described in detail in this subsection. Specifications of major components and vendors are listed in Section 5.

3.2.1 Fan, Motor, and Coupling

The fan selected is an airfoil-blade, centrifugal blower designed to produce a 12-inch static pressure rise at 2350 rpm, moving 17,000 scfm of air. The fan will operate at temperatures up to 500°F, with 17,000 acfm provided at this higher temperature. Additional features of the fan include a large inspection door with quick-opening latches, flanged inlet and outlet openings, and a drain coupling at the bottom of the housing. The fan is entirely insulated to prevent thermal energy loss and personnel burns. All surfaces exposed to the test gas are constructed of 304 stainless steel to prevent corrosion and subsequent entrainment of rust particles in the test gas. The fan is driven by a V-belt drive to an eddy current coupling and a 50 HP, squirrel cage induction motor. The motor and eddy current coupling are an integral unit, with the motor operating at a constant 1800 rpm and the output shaft from the coupling operating at 50-1715 rpm. The eddy current coupling is controlled with a solid state SCR-type controller which is wall-mounted nearby.

The fan exhausts into a diffuser and large duct section which is described in the next subsection.

3.2.2 Duct

Flow from the fan is directed toward the gas conditioning equipment by a 6'0" by 6'0" duct, as shown in drawing M-2. The inlet end of this duct is a straight-walled diffuser which brings the flow to the low velocities desired at the air conditioner and heater. The duct walls are strengthened with 2-inch by 1/4-inch bar stock, on edge, tack-welded around the circumference of the duct every 2'0" along the duct axis. Access to the interior of the duct for cleaning or maintenance is provided by a single hatch in the side of the duct.

3.2.3 Gas Conditioning Section

The gas conditioning section is a removable section of the 6'0" by 6'0" duct (drawing M-3). It includes all of the cooling, humidifying, and heating apparatus for the tunnel operation. The cooling and humidifying apparatus will be designed and installed by an air conditioning subcontractor. Consistent with the conclusions of Section 2.4.7, the air cooling will be accomplished with a chilled water coil (drawing M-4). The coil is constructed of hard-drawn, 5/8-inch O.D. copper tubing with aluminum fins. Tubes will be arranged in a staggered pattern for maximum thermal efficiency. A small pump will move up to 36 gpm of 45°F chilled water, which is provided on-site, through the coils. The system is designed to remove approximately 150,000 Btu/hr. This heat exchanger will be specially constructed to fill the entire 6-foot by 6-foot cross-section of duct at this section. Downstream of the cooling coils, a dry steam humidifier will be installed, as shown in drawing M-4. Up to 76 lb/hr of 15 psig steam, provided on site, will be injected automatically into the air flow. Steam passes through a separator ahead of the control valve to eliminate "spitting" or condensate from the injection manifold. The injection manifold is steam jacketed as well, to prevent condensation. The steam injection is controlled with a pneumatically actuated control valve. A temperature switch is also included to prevent the humidifier from coming on before it is entirely warmed up. The air conditioning system will use the large duct heater designed for hot flow runs when any reheat is necessary. This section of duct, which contains the water coil, humidifiers, and heater, will be built as a separate assembly and installed as a unit. It can be removed easily for maintenance or configuration changes.

The duct heater is described in the next subsection.

3.2.4 Duct Heater

The heater is designed for steady state operation of the tunnel at test gas temperatures controllable between room temperature and 450°F in the test section. The full temperature range can be achieved at all required flow rates, from 950 to 17,000 cfm. The heater is designed to provide reasonable start-up times (maximum of 2-3 hours) or any desired operating condition within the specified range.

The limits of operating conditions are presented in Table 7.

TABLE 7

WIND TUNNEL HEATER REQUIREMENTS

Variable	Max Flow	Min Flow
	Steady State Operation	
Test Gas Flow Rate (ft^3/sec)	280	16
Heater Temperature (°F)		
Outlet	80-450	80-500
Inlet (at Hottest Condition)	450	80
Power Input (kw)	95	70
	Initial Heat Up	
Power Input (kw)	200	--
Time to Stabilize (hr)	2-3	--

The steady state power requirements and heater inlet temperatures are based on computed heat leaks through 2 inches of standard duct insulation on all exterior surfaces of the duct system (including the particle collector). Insulation exterior surface temperatures will nowhere exceed 150°F. At the low flow condition, the test gases will enter the heater section at virtually room temperature due to the effect of heat leaks on the relatively small mass of gas circulating. A 50°F drop in gas temperature is expected in the distance between the heater and test section at the lowest flow condition. However, this will present no difficulties because the thermostat will be located at the test section inlet. It should also be noted that free convection will cause some temperature stratification in the low flow range. Mixing in the ductwork preceding the test section will help to alleviate the stratification problem.

Tunnel start-up for elevated temperature operation is most efficiently achieved by operating the tunnel at a high flow rate until stabilization is attained at the desired temperature and then reducing the flow to the desired level. The heater would become excessively large and expensive if it were required to provide the full 200 kw in the low flow rate range.

An electric heater was selected over a gas-fired heater for the wind tunnel design on the basis of: (1) lower operating cost, using a readily available source of energy; (2) more accurate control; (3) better temperature uniformity; (4) clean operation; (5) low maintenance; and (6) long lifetime. The heater will be located as shown in drawing M-4 in the 72" x 72" duct section between the blower and the test section. Heater control will be automatic such that the test section temperature may be maintained accurately by setting the desired temperature at the test section entrance. Characteristics of the heater and its control system are summarized in Table 8.

It should be noted that the price of the heater and control system (~$7000) could be reduced by nearly 50 percent if 440v, 3φ power was available. This higher voltage power is not available at present, however.

3.2.5 First Elbow

Flow from the gas conditioning section is directed around a corner to the settling chamber by an elbow, shown in detail in drawing M-5. Circular arc turning vanes with a leading edge angle of attack of 4°-5° and a trailing edge angle of 0° direct the flow smoothly around the corner. Turning vanes are tack-welded in position and are constructed of light gage stainless steel, since aerodynamic loads are small in this large cross section. Flow coming out of the corner then passes through the "square-to-round" transition, where the cross-section changes from a 6'0" by 6'0" square to a 6'0" diameter round

TABLE 8

HEATER AND CONTROL CHARACTERISTICS

Type	Electric, 230V, 3ϕ, 60 cycle wired in 1 circuit
Maximum Power	200 kw
Heater Elements	54 corrosion-resistant alloy sheathed hairpin tubular elements, each 0.5" O.D. by 152" long
Heater Dimensions	71-1/4" by 71-1/4" by 8" inside the duct, flange-mounted with attached terminal box assembly
Indicating Temperature Controller	All solid state automatic set-point temperature controller operating on iron constantan thermocouple output measured at test section entrance
Power Controller	Saturable core reactor
Proportioning Band	May be varied down to ±1/2°F
Overtemperature Control	Circuit breaker has trip shunt operated if overtemperature occurs on heater elements
Startup Control	Pressure-type air flow indicator upstream of fan prevents heater operation without proper airflow

section. Access to the interior of this elbow after installation is provided by a hatch upstream of the turning vanes, and another hatch downstream of the turning vanes.

3.2.6 Stilling Chamber

The stilling chamber is a 6'2" diameter, 2'8" long cylinder, shown in drawing M-6. The round cross-section in the stilling chamber allows the flow to progress smoothly into the contraction and test section without any further change in cross-section shape, thereby minimizing turbulence generation near the walls. Two screens and one honeycomb (drawing M-7) are installed across the stilling chamber which aid in damping turbulence in the tunnel flow. The honeycomb material is commercially available stainless steel hexagon, with a 1-inch cell width and a length of 6 inches. The screens are located 2 and 9 inches downstream of the honeycomb, respectively and are 16 mesh, 28 swg stainless wire (drawing M-8). The screens and honeycomb are installed in such a manner as to present a smooth, 6'0" cylindrical surface to the flow at the walls of the stilling section. The honeycomb is installed on a 6'1-15/16" hoop, as shown in drawing M-7, with a welded steel frame giving the honeycomb rigidity in the flow direction. The screens are clamped on a 6'0" I.D. hoop with a small amount of tension in the screen to smooth wrinkles and eliminate sag. The screens and honeycomb can be removed through the hatch in the first elbow (downstream of the turning vanes).

3.2.7 Dust Feeder

a. Dust Generation and Metering

The proposed dust generation and metering is considered to be developmental in nature and no doubt will be modified at a later date. The system consists of a live-bottom bin, hand-actuated slide valve, and an aspirator. The live-bottom bin has a 50 cubic foot capacity, is 48 inches in diameter, and has an overall height of 6'6". The outlet orifice of the bin is 1'10" from the laboratory floor. The bottom of the bin is vibrated by a 1.5 HP motor. The bin is constructed of 304 stainless steel. Loading is accomplished manually.

Metering of the dust flow rate is done by hand-setting a sliding plate valve at the bottom of the bin (Figure 30). Precision adjustment is possible by rotating the knurled knob, which in turn slides the metering plate and uncovers more (or less) of the diamond-shaped orifice. Major changes in the dust feed rate can be accomplished by installing different sized orifices and metering plates.

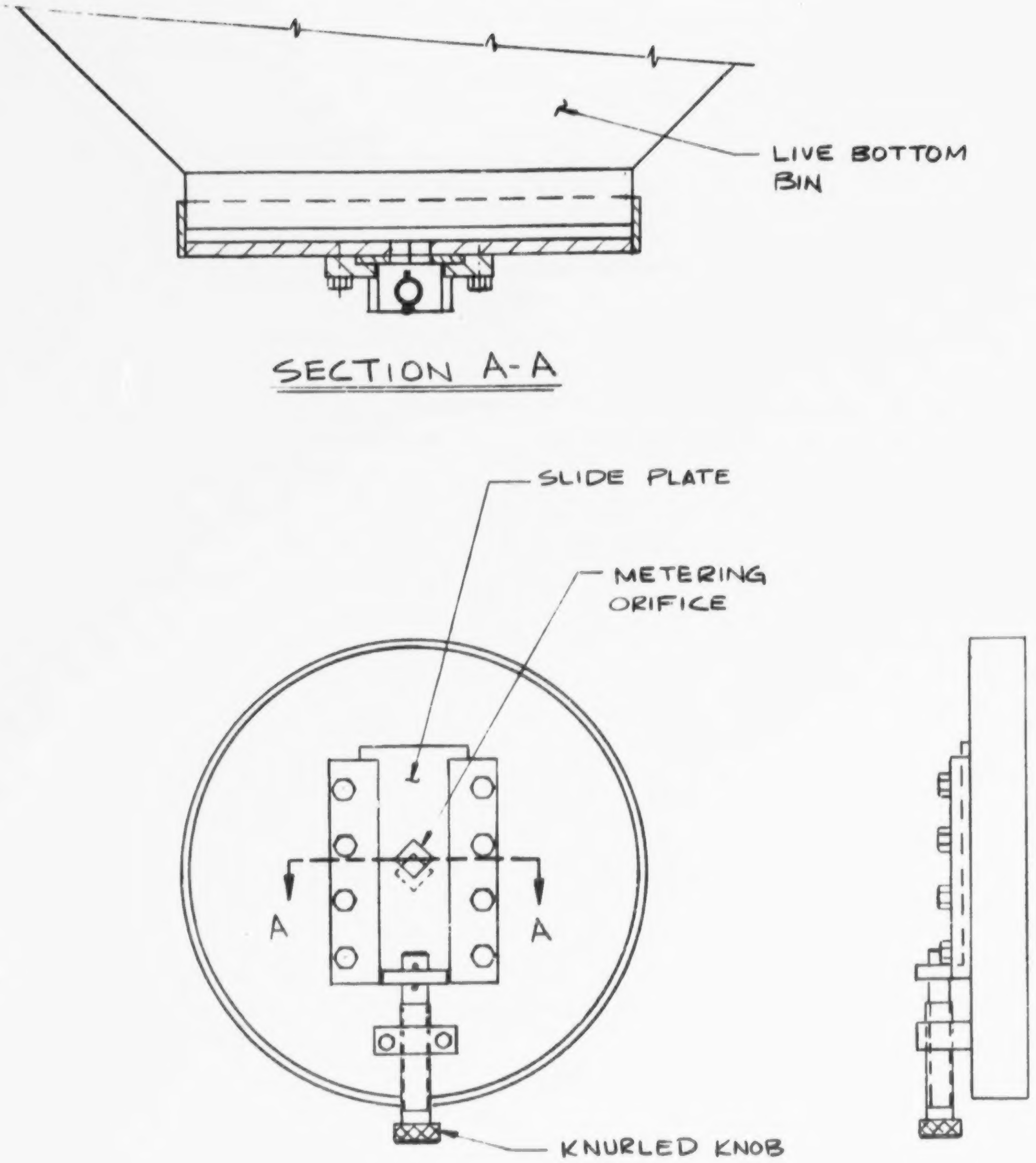

LIVE BOTTOM BIN
SECTION A-A
SLIDE PLATE
METERING ORIFICE
A
A
KNURLED KNOB

FIGURE 30. DUST METERING VALVE

A-3936

The dust aerosol is created by directing the dust through the metering plate into a 3/4-inch air aspirator (Figure 31). The carrier gas flow rate is controlled by a valve upstream of the aspirator. Carrier gas is also ionized downstream of the aspirator to avoid dust agglomeration in the dust injector lines. The dust aerosol is then directed into a manifold which divides the flow into seven separate streams for the seven injectors. The manifold is designed to avoid accumulation of dust in corners or bends, and to avoid "preferential" flow of the carrier gas into any one tube. The particular aspirator considered has been used with satisfactory results in another test facility.[5] In that application, a good aerosol free of agglomerates was obtained working with flyash dust delivered at rates up to 2 pounds per minute. It is not known whether this aspirator can manage 12 lb/min. This will have to be determined experimentally.

All pipe or tubing sizes are selected to keep the carrier gas velocity above 4000 ft/min at the lowest flow rate.

b. Dust Injection

Each dust injection tube which leads from the manifold incorporates a short section of flexible tubing. Fine adjustments of the flow rate through each injector can then be made by clamping the appropriate tube or tubes slightly. The dust and carrier gas then passes through the tunnel wall and out into the gas stream through the seven injectors, shown in drawing M-9. All injector tubes are led to the center hub of the assembly through a pipe with an airfoil fairing, which minimizes turbulence from the pipe. The tubes then fan out to form a star-shaped pattern, and the aerosol is injected through cone-shaped nozzles. The cone angle of the nozzles is shallow enough to avoid flow separation, therefore a smooth deceleration of the carrier gas and dust to the stilling chamber velocity is anticipated. However, the nozzles are threaded onto the injection tubes for possible system modifications at a later date. Also, ready access to the injection system is provided by removing the honeycomb and screen assemblies from the upstream side.

3.2.8 Contraction

The contraction (drawing M-10) is a converging section which provides an area ratio from inlet to outlet of 9:1, going from a 6'0" to a 2'0" diameter over a length of 7'6". The contraction shape was designed by the method of Cohen and Ritchie,[22] and provides a smooth acceleration of the flow with minimal adverse pressure gradient at the wall near the test section end. The upstream end is flanged for ordinary bolt attachment, while the downstream end has a tapered flange for use with the Marman clamps to be used with the test section duct.

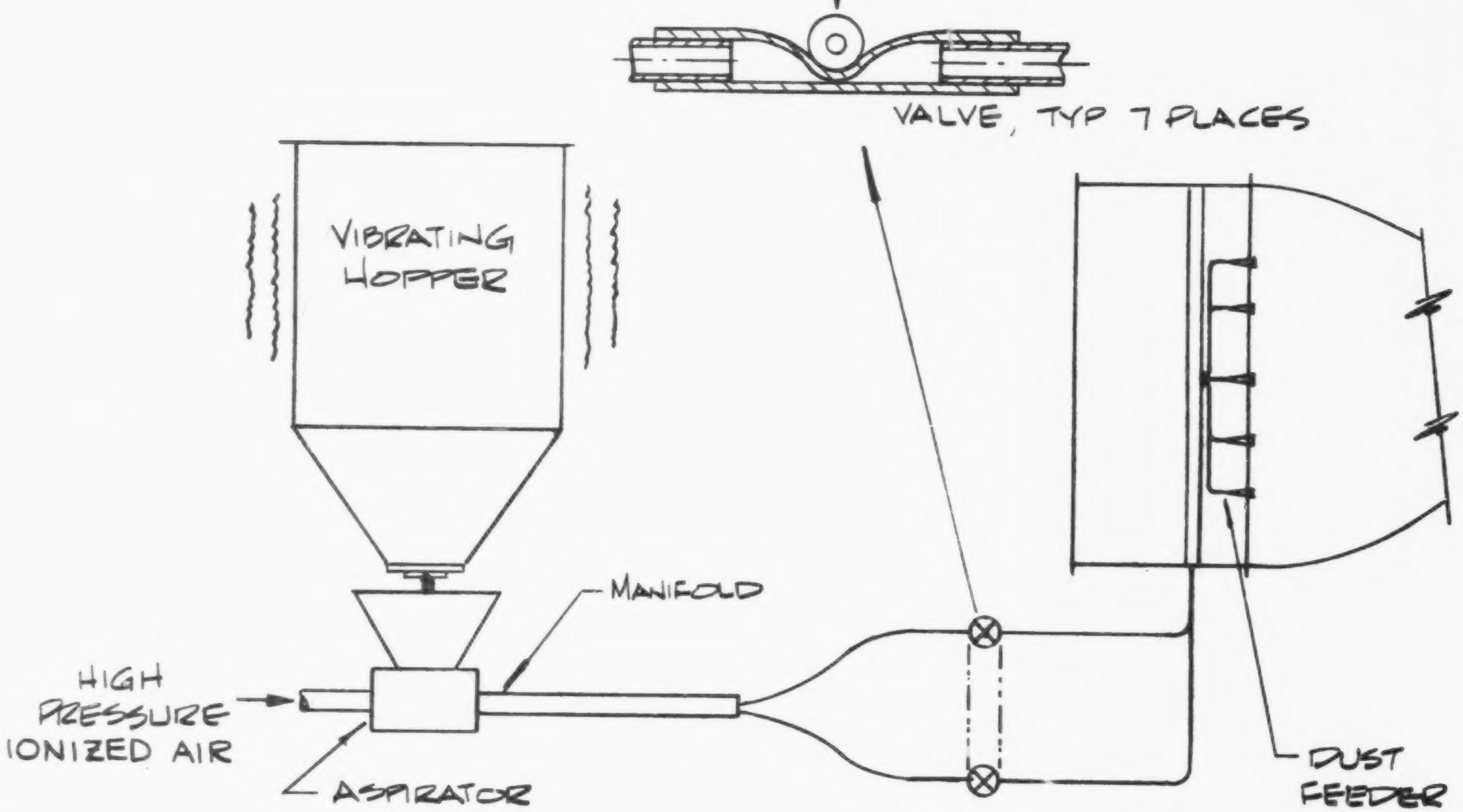

VALVE, TYP 7 PLACES
VIBRATING HOPPER
MANIFOLD
HIGH PRESSURE IONIZED AIR
ASPIRATOR
DUST FEEDER

FIGURE 31 NOZZLE DUST FEED SYSTEM

3.2.9 Test Section

The test section is composed of five lengths of 2'0" diameter, stainless steel duct. Three of the pieces are 10'0" long (drawing M-11) and two are 5'0" long (drawing M-12), giving a total length of 40'0". The segments of the test section are connected with Marman-type clamps, which allow a rapid release and removal of any or all segments for configuration changes, model installation, or cleanout. To facilitate movement of the duct sections, each is mounted on a cart (drawing M-1). The carts support the duct sections on specially constructed saddles which allow vertical adjustment to align the segment.

The 5'0" duct sections are intended to enclose the model, instrument, or test fixture. The shorter length allows the model to be installed from either open end, with additional access provided through the window openings. The 5'0" sections each contain four 7-3/8 inch diameter window openings: two in the horizontal plane and two in the vertical plane. The window opening receives the window flange (drawing M-13) which bolts directly onto the tunnel wall. The window flange provides a flat surface against which the 3/4-inch flat quartz window is clamped and sealed with O-rings. The final window opening with this assembly is 5-1/4 inch in diameter. While the windows are flat and intrude upon the flow area slightly, the expense associated with fabricating and installing curved windows is not justified.

The 10'0" sections each have two windows, similar to those described above, in the horizontal plane. It will be noticed that no general instrumentation ports are provided. Such ports, such as for a stack sampling probe, could easily be adapted to the window openings, or through additional holes in the duct. Provision for instruments, models, probes, etc. can be installed at a later date when a particular test program is designed.

3.2.10 Flex Coupling Section

The flex coupling section (drawing M-14) forms the first component of the flow return circuit. It consists of two 90° corners with a 2'0" diameter connecting duct. The inlet to this duct section is screened with large mesh (1/4"-1/2"), rigid screen to catch loose objects from the test section. The 1-inch slot near the duct entrance is manifolded and vented to ambient, providing the wind tunnel vent discussed earlier.

Turning vanes are installed in each corner to minimize corner pressure losses, which are large due to the high local velocity, and improved the velocity distribution in the diffuser. Due to floor space constraints it was not possible to diffuse the flow from the test section before entering the first corner. The turning vanes in this section are similar in design to those described earlier. However they must be welded at the ends along the entire arc to insure firm support in the aerodynamic loads which will occur in these corners.

The two metal bellows in this duct section provide flexibility which will be required for thermal expansion and for alignment.

3.2.11 Diffuser

The diffuser (drawing M-15) is a simple cone shape, 39'10" long, changing from a 2'0" diameter to a 6'0" diameter. This results in a 5.75° cone angle, which is near the optimum diffuser angle for a wind tunnel of this type.[19] The diffuser saves approximately 10-15 percent on the tunnel power requirements by recovering a large portion of the kinetic energy of the test stream.

3.2.12 Elbow to Baghouse (Drawing M-16)

This elbow in the return circuit directs the flow into the baghouse. Its flat-sided design allows simple fabrication techniques and maximum cross-sectional area for the flow, thereby minimizing pressure loss. A large mesh, expanded-metal gridwork at the outlet of this elbow prevents personnel or tools from falling into the baghouse.

3.2.13 Baghouse (Drawing M-17)

Particle collection for this wind tunnel will be accomplished by a baghouse permanently installed as part of the flow loop. The baghouse dust collector is the only type of collector which offers the level of efficiency required in a recirculating gas flow, for a reasonable price. The baghouse is constructed for operation at temperatures up to 425°F, using 16-ounce Nomex or equivalent high temperature bag material. The air-to-cloth ratio of approximately 7.5 is allowable for this application, since the facility will not be in production use. The baghouse is self-cleaning, with solenoid actuated reverse flow air jets.* Frequency of the reverse-flow air jets can be varied by the operator with an external timer setting. Dust from the collector bags falls to a hopper which runs the length of the baghouse, and is moved out of the hopper by a rotating vane airlock. A screw conveyor then moves the dust along the length of the baghouse, where it can be dumped into a container.

---

*It is assumed that the cleaning action will be turned off during actual data-taking. If data gathering activities will extend over long periods of time, a different type of bag cleaning should probably be considered.

The baghouse is constructed of ordinary carbon steel on the dirty air side, but uses stainless steel on the clean air side. The hopper is modified on the intake side (drawing M-17) to receive the inlet pipe. This custom made inlet maximizes the flow area, thereby minimizing the pressure loss as the flow expands through the opening. The baghouse will be delivered from the vendor with 2 inches of insulation material, covered with a thin aluminum skin, on all panels. Other features supplied by the vendor include motors and drives for the air lock and screw conveyor, and access doors for bag maintenance.

The baghouse flow exit is also modified as shown in drawing M-17 to increase the cross-sectional area and minimize pressure loss.

3.2.14 Duct from Baghouse to Fan (Drawing M-18)

Flow is directed from the baghouse to the fan inlet by a large rectangular duct section. This duct section has a cross-section approximately equal to the baghouse outlet. Each corner has turning vanes to maintain a uniform flow leading into the fan. A rectangular-to-round section and a bellows then leads the flow to the fan inlet.

3.2.15 Tunnel Inlet, Exhaust, and Open Circuit Valves

The wind tunnel is connected to the outside air by two parallel ducts and associated valves on the high pressure side of the fan, as shown in Figure 32 and drawing M-2. These ducts allow the tunnel to be purged of exhaust products at the end of a test run by opening the valves in the inlet and exhaust ducts and closing the "open-circuit" valve. The open-circuit valve is a shutter which is permanently installed in the 6'0" by 6'0" duct section downstream of the fan. With the open circuit valve closed and the inlet and exhaust valves open, fresh air enters the system, traverses the entire flow loop, and exits again as shown schematically in Figure 33. Valves are actuated by small electric motors which are operated from the control console. The exhaust valve is also opened slightly when the burner is in operation, as described in the next subsection.

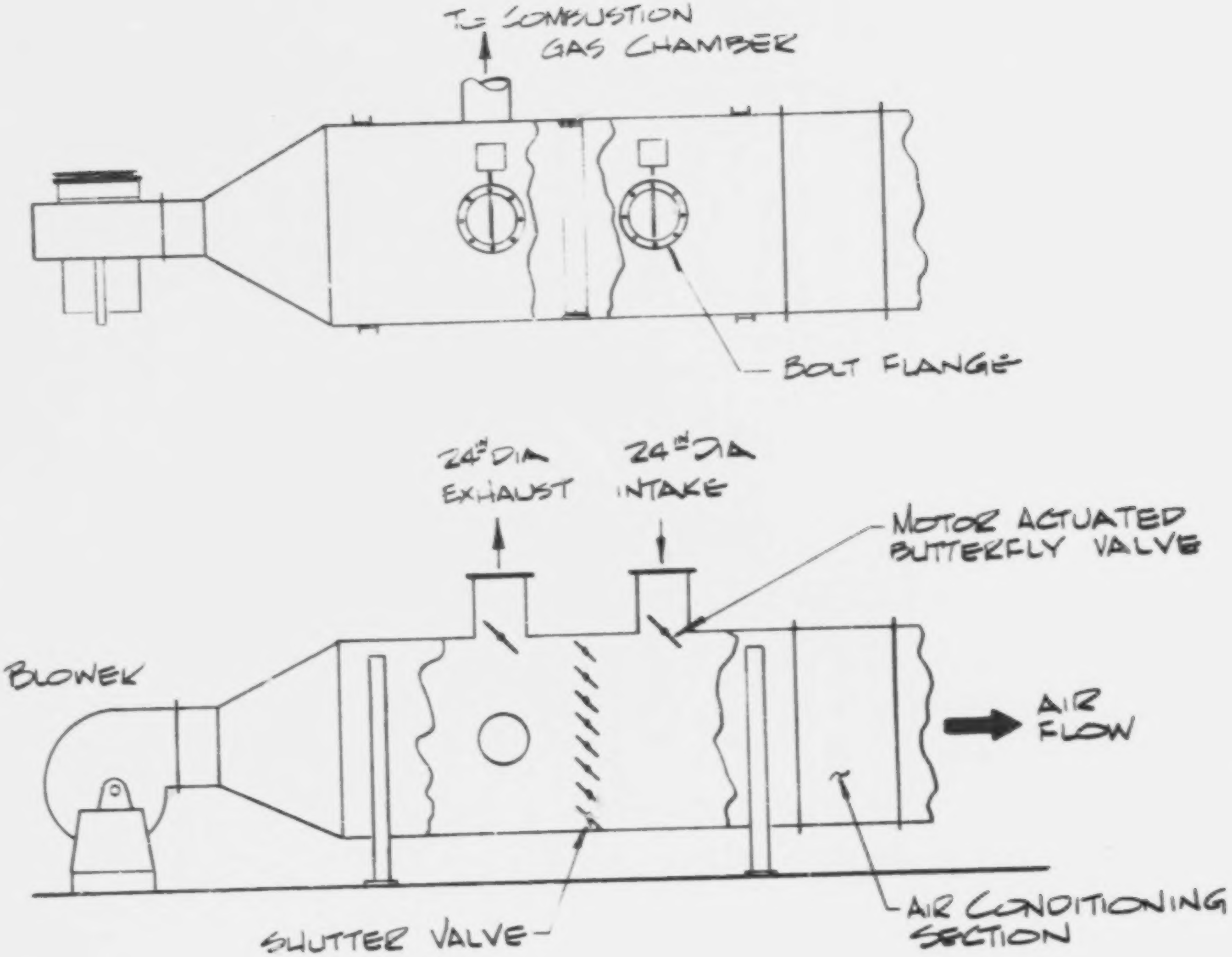
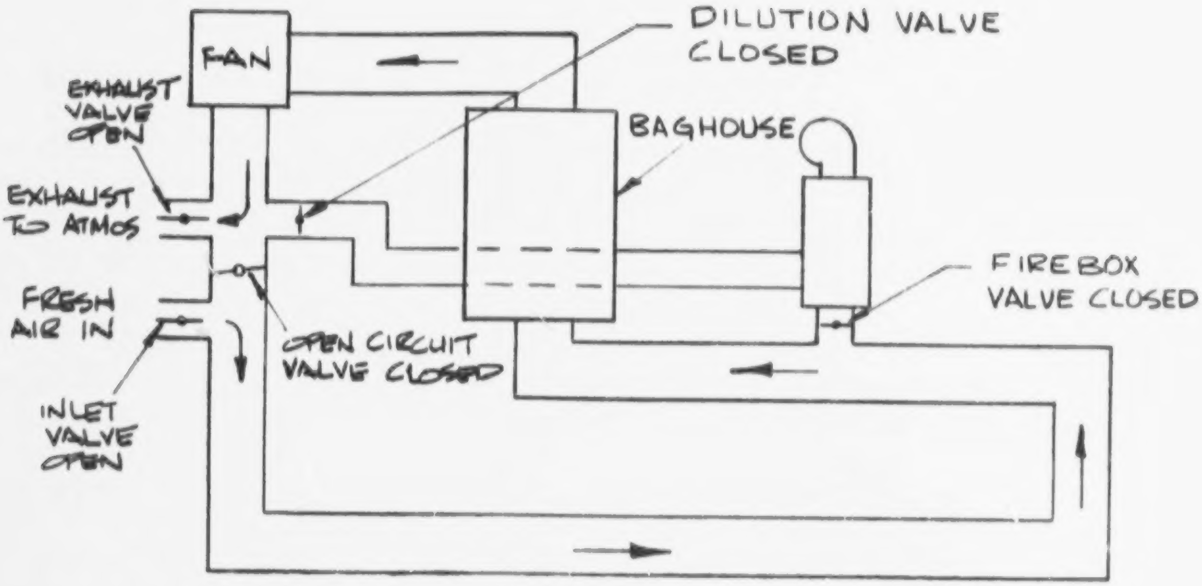
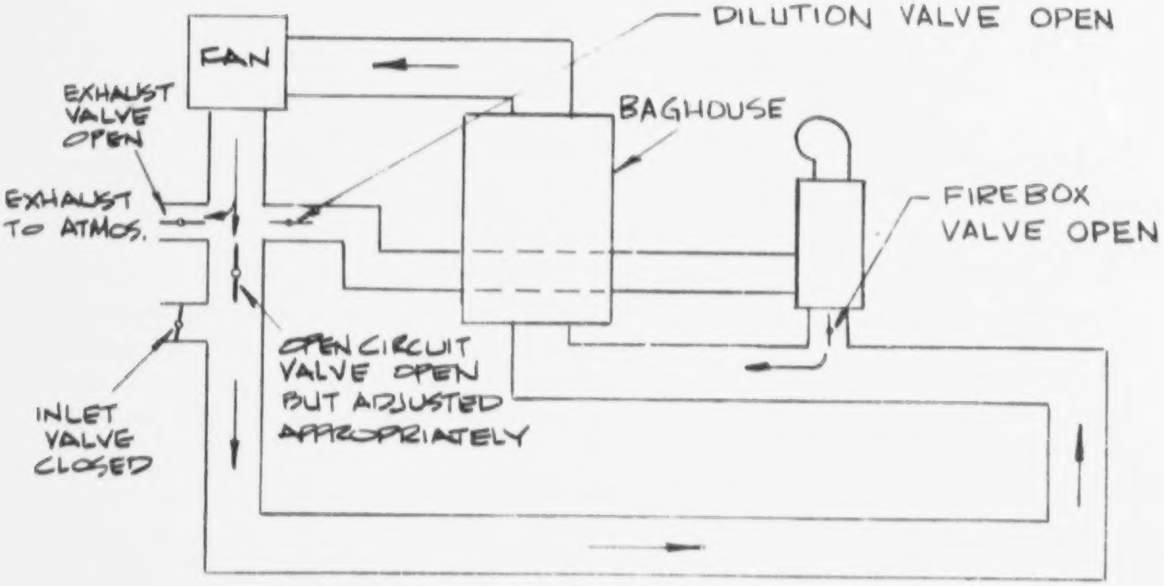

TO COMBUSTION GAS CHAMBER
BOLT FLANGE
24" DIA EXHAUST
24" DIA INTAKE
MOTOR ACTUATED BUTTERFLY VALVE
BLOWER
AIR FLOW
SHUTTER VALVE
AIR CONDITIONING SECTION

FIGURE 32. INLET, EXHAUST, AND OPEN CIRCUIT VALVES


DILUTION VALVE CLOSED
FAN
EXHAUST VALVE OPEN
BAGHOUSE
EXHAUST TO ATMOS
FRESH AIR IN
FIREBOX VALVE CLOSED
OPEN CIRCUIT VALVE CLOSED
INLET VALVE OPEN

A) VALVE SETTINGS FOR PURGING THE TUNNEL


DILUTION VALVE OPEN
FAN
EXHAUST VALVE OPEN
BAGHOUSE
EXHAUST TO ATMOS.
FIREBOX VALVE OPEN
OPEN CIRCUIT VALVE OPEN BUT ADJUSTED APPROPRIATELY
INLET VALVE CLOSED

B) VALVE SETTINGS FOR FILLING TUNNEL WITH COMBUSTION PRODUCTS

FIGURE 33 VALVE ARRANGEMENT FOR OPEN CIRCUIT AND GAS FILLING OPERATIONS.

3.2.16 Combustion Products Burner and Firebox

a. Burner and Blower

The burner which is used to fill the tunnel with exhaust products is a dual fuel unit for operation on either natural gas or light distillate fuel oil. Nominal energy release is 2,000,000 Btu/hr, corresponding to fuel flow rates of 15 gph of oil and 2500 scfh of natural gas. Excess air should be held to a minimum.

The air blower is an integral part of the burner. A shutter provides air flow rate control. This will not be actively controlled, but will be set initially to operate at an optimum air/fuel ratio. Since the burner back pressure will not change, no active control of air flow is needed. A description of the burner safety interlock systems is provided in Section 3.3.8.

b. Firebox (Drawing M-19)

The burner firebox will be specially constructed. Since the burner will be run at a minimum of excess air, the inner surface of the firebox should be a super-duty firebrick useful in roughly the 2800°F to 3000°F range. Since thermal losses from the firebox are of no practical consequence, the firebox need not be well insulated, and a standard 4-1/2 inch thickness will be adequate. This will yield an outer wall temperature of about 500°F, which will be tolerable provided that operating personnel are kept away from the hot surface by suitable screening provisions and also that the firebox does not rest on a concrete floor. The location of the burner/firebox assembly is shown in drawing M-2. Note that dilution air is brought in from the high pressure side of the wind tunnel fan and injected into the firebox downstream of the burner flame. As discussed earlier, this dilution air is necessary to cool the exhaust products down to a useable temperature. Approximatley 2500 scfm of dilution air will be used. Indication of the dilution air flow rate will be provided by a venturi section and associated pressure indicator in the dilution air supply pipe, with readout at the control console. Drawing M-19 shows a firebox of appropriate inner dimensions for the heat releases of interest, with additional length for mixing of the dilution air. The firebox may be constructed either of bricks or of monolithic (casting or molding) refractory; the one shown is of brick. In either case the end wall in which the burner is mounted will be at least partly of monolithic construction to allow an exact mounting of the burner. The firebox will be jacketed in 10 or 12 gage steel to allow handling and mounting on the support structure.

c. Exhaust to Diffuser

The diluted combustion products will be exhausted to the diffuser through an exhaust duct (Figure 34). The duct terminates at a motor actuated valve which closes flush with the diffuser wall, giving a clean aerodynamic surface during tunnel operation.

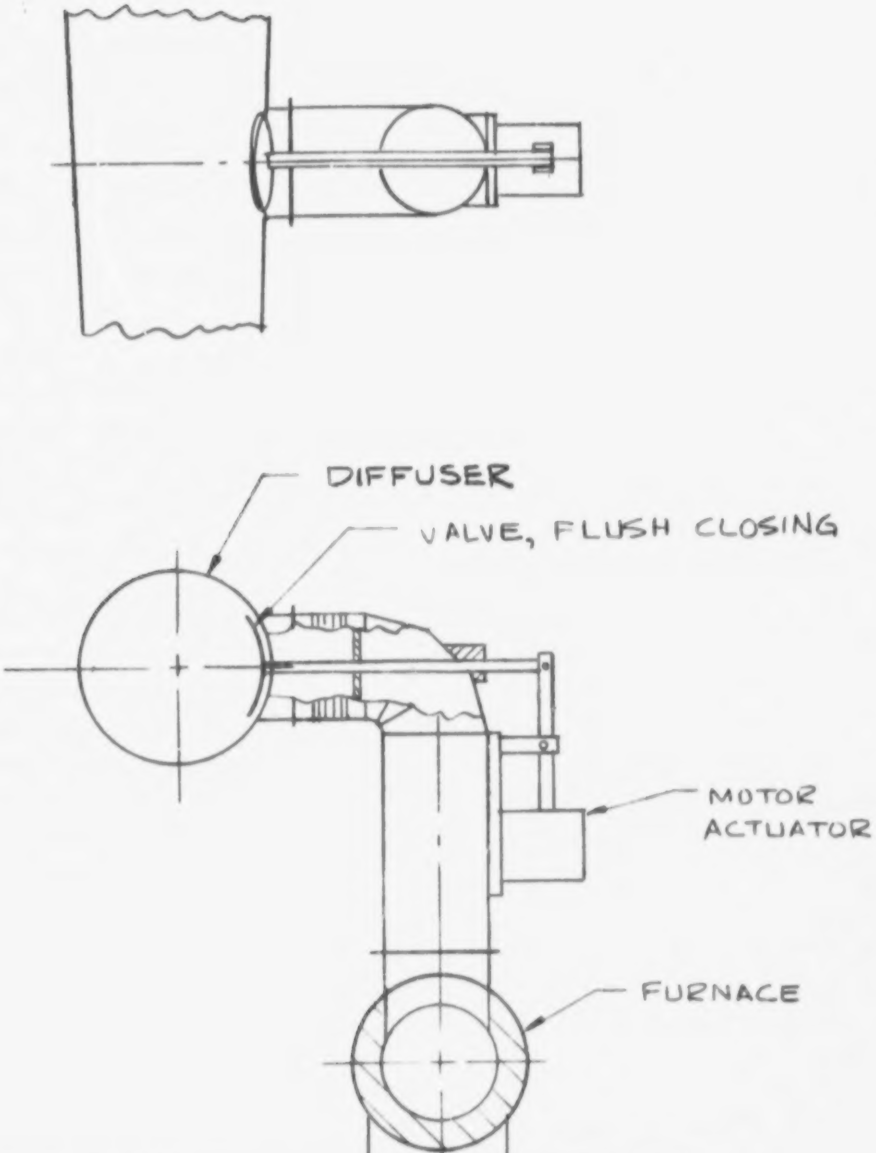

DIFFUSER
VALVE, FLUSH CLOSING
MOTOR ACTUATOR
FURNACE

FIGURE 34. FIREBOX EXHAUST DUCT AND VALVE

3924

3.3 CONTROLS AND INSTRUMENTATION

The controls and associated instrumentation for this wind tunnel are much more complex than for an ordinary tunnel, where only velocity is controlled. In the present system, the following quantities are automatically controlled, usually simultaneously.

- Test gas velocity
- Test gas temperature
- Test gas humidity
- Test gas composition
- Dust feed rate
- Dust carrier gas flow rate
- Burner operation
- Burner combustion products dilution
- Baghouse cleaning frequency
- Inlet, exhaust and open-circuit valve settings

It is not possible to describe a complete control and instrumentation system without carrying out the detailed mechanical and electrical designs for this facility, which were not called for under this contract. However, it is possible to discuss the system controls in a general way, and to indicate how the design should be carried out. This general discussion is presented below. It begins with a discussion of the control console, then describes control of each variable.

3.3.1 Control Console

Control over most of the system components can be carried out from a control console, drawing M-20. This console contains on-off or open-close buttons (green light when on) for the following equipment:

- Fan motor
- Cooling water pump
- Humidifiers
- Duct heater
- Dust feeder
- Burner blower
- Burner igniter

- Baghouse screw-conveyor
- Baghouse rotating air-lock
- Tunnel inlet valve
- Tunnel exhaust valve
- Tunnel open-circuit valve
- Dilution air valve
- Firebox exhaust valve

The control console contains set-point controllers for

- Velocity in the test section
- Temperature in the test section
- Humidity in the test section
- Baghouse reverse jet frequency

The control console contains indicators or meters for the following variables

- Test section velocity
- Temperature at seven positions in the flow circuit
- Test section humidity
- Air pressure at three locations
- Facility steam pressure at the humidifier inlet
- Water pressure at the chiller inlet
- Dilution air flow rate

Since much of the equipment is interlocked, a series of fault lights is also installed on the console. Each fault light indicates the condition of a particular system interlock. Ten fault lights are currently planned, which indicate the following faults.

1. Fan motor - cooling air blower not operating
2. Fan motor - fan not rotating
3. Fan motor - air temperature too high
4. Fan motor - open circuit valve closed, inlet and exhaust valves not open
5. Chilled water pump - no water flow
6. Humidifier - no steam flow
7. Duct heater - no air velocity through heater elements

8. Duct heater - element overheat

9. Daghouse - gas temperature too high

10. Burner - any one of a series of interlocks on the burner is not satisfied. Burner faults are listed later in this section.

Two other fault lights are indicated on the panel, to be connected to dust feeder operation at a later date.

The console also includes a writing shelf, an air pressure regulator for the pneumatic instruments, and the duct heater controller.

3.3.2 Velocity Control

The conventional way to measure velocity in a wind tunnel, and the way it will be measured in this facility, is to measure the static pressure decrease between the plenum and the test section. Then, for any measured ΔP

$$V = \sqrt{\frac{2\Delta P}{\rho}}$$

where

$\Delta P = P_t - P$

P_t = total pressure or pressure in the stilling chamber

P = static pressure in the test section

ρ = density in the test section

Density is generally found from the perfect gas equation

$$\rho = \frac{P}{\frac{R}{\mathcal{M}} T}$$

where

R = universal gas constant

$\mathcal{M}$ = molecular weight

T = temperature

The dust loadings in this facility are not great enought to affect the local molecular weight significantly, therefore only the gaseous components need be considered. Temperature does vary, so it must be measured in the test section as well as static pressure.

Electrical controls in the present facility design are indicated in block diagram form in drawing M-21. The desired velocity will be set with a dial-type potentiometer, POT 1, on the control console and the fan will be turned on (PB1). The set-point signal will be fed into a small analog computer, along with the readings from the ΔP pressure transducer and the thermocouple which senses temperature at the desired station in the test section. The computer then calculates an error signal, which is fed to the eddy current coupling speed control unit. The speed in the tunnel is then automatically held at the preset value to within 0.5 percent. Actual velocity in the test section is indicated on the control console on the indicating velocity meter, VMR1. While transient behavior of the tunnel can be caused with the set-point controller, neither the tunnel nor the controller is designed for rapid transient response.

3.3.3 Test Gas Temperature

Temperature will be measured in this facility at a number of locations with thermocouples. At present, seven locations are planned, which include

- One location in the test section
- At the inlet to the baghouse
- In the combustion chamber
- In the duct downstream of the burner
- At the fan outlet
- In the duct downstream of the heater
- In the stilling chamber

All of these temperatures will be displayed continuously on the control console In addition, interlocks will shut off the burner and heater if temperatures exceed the design upper limits.

Heating of the test gas in the facility will be accomplished by the electrical duct heater, the saturable core reactor, and the control unit. The desired set-point temperature is set (CON1) on the control console and the heater unit is actuated (PB2). The actual temperature in the test section will be sensed with a thermocouple. The heater control unit will compare these two signals and control the power to the heater accordingly.

For cold runs, temperature is controlled by the chilled water cooling system and pneumatic controller (CON2). The cooling water pump is actuated with PB8. The dry bulb temperature reading in the plenum is sensed by a thermocouple and compared to the desired temperature set on the controller. The error signal is transmitted to the pneumatically actuated three-way valve (drawing M-22) which controls chilled water flow. More or less water is then routed to the chiller as required.

3.3.4 Test Gas Humidity

The humidifier is actuated along with the chilled water pump (PB8). Control of the relative humidity (CON2) requires a relatively "clean" air stream, therefore wet bulb and dry bulb temperatures will be sensed in the plenum, ahead of the dust injectors. Wet bulb temperature is sensed with a porous Alundum sensor. The pressure levels which are generated by the pneumatic-type wet and dry bulb sensors are fed to the humidity control unit, which then compares the resulting humidity level to the set point, and actuates the steam injectors accordingly. Both the dry bulb temperature and the relative humidity are controlled by a single controller during cold runs. The controller also provides a circular chart record of the dry bulb temperature and humidity level in the tunnel.

3.3.5 Test Gas Composition

Test gas composition is controlled by the operation of the burner (Section 3.3.8). The initial charge of air in the tunnel is recirculated at the maximum tunnel speed, and the exhaust valve is opened slightly. The burner is then operated with the burner exhaust emptying into the tunnel. As the burner continues to operate, the level of CO_2 and H_2O in the tunnel will continue to rise until it approaches 100 percent exhaust products, as explained in Section 2.4.8. Composition of the test gas can be sensed at the test section with existing APCO instrumentation, therefore, these instruments are not included in this design study. It is also felt that it would be unwise to attempt to control composition automatically at this time in the facility development, therefore it is assumed that startup and shutdown of the burner and setting of the various valves will be done manually.

The composition of the test gas can also be altered by injection of bottled gas near the fan inlet, if compositions other than that supplied by the burner are desired. No special provisions for this approach have been included due to the simplicity of the necessary alterations.

3.3.6 Dust Feed Rate

Due to the preliminary nature of the dust feeder design, and the need for an experimental development program to arrive at an optimum feeding system, the dust feeder will be operated as a stand-alone system, independent of the operation of the rest of the tunnel. At a later date, dust feeder operation can be coupled to the tunnel velocity, and all control will be carried out at the control console.

In the proposed design, the live-bottom bin is actuated from the control console (PB7), as is the baghouse airlock and screw conveyor (PB5 and PB9). Dust feed rate is then controlled by manually setting the position of a slide valve at the bottom of the bin, which changes the size of an orifice opening through which the dust falls.

3.3.7 Dust Carrier Gas Flow Rate

The dust carrier gas flow rate should be adjusted with the tunnel velocity to maintain an isokinetic injection condition. This is accomplished by manual adjustment of the valve which controls flow to the aspirator, drawing M-22. Final small adjustments in each dust injector line to equalize the flow out of each ejector can be made with individual clamp valves on flexible tubing portions of the feeder lines located outside the stilling chamber.

3.3.8 Burner Operation

The burner operates in an on-off mode only, with no provision for automatically adjusting the air-fuel ratio, flow rates, or other burner variables. The installation will result in a clean-burning, smokeless, "blue-flame" burner operation, thereby avoiding problems with large amounts of soot in the tunnel circuit.

To actuate the burner, the tunnel must be in operation and the valve which allows combustion products to flow into the diffuser must be opened (PB12). The dilution air duct must also be opened (PB11). The burner-blower start button, PB3, and the igniter button, PB4, are then depressed. Burner control is then transferred to the burner control center, a panel near the burner itself, which carries out the start sequence. The burner control center includes a flame safeguard and other interlocks which do not allow fuel flow unless all systems are operating properly. The flame safeguard logic incorporates standard flame safety logic elements:

- Flame-out detection and associated mandatory purge periods after flame-out.
- Trial-for-ignition period and associated transfer to flame-out detector.
- High or low ignition voltage interlock.

In addition, several other interlocks are provided to interrupt fuel flow for the following conditions:

- Low or no velocity in the tunnel
- Firebox exhaust valve closed

- Insufficient dilution air flowing
- Low combustion air pressure
- High/low firebox pressure
- Low fuel pressure
- High firebox temperature
- High diffuser duct temperature

3.3.9 Baghouse Cleaning Frequency

The frequency with which the reverse jet cleaning action of the bags occurs is controlled with a timer, mounted on the control console.

3.3.10 Inlet, Exhaust and Open Circuit Valve Settings

The inlet, exhaust, and open circuit valves are opened at the conclusion of an exhaust products run to purge the tunnel of combustion products. The exhaust valve is also opened during filling the tunnel with exhaust products from the burner. The valves are actuated electrically, and are controlled individually from the control console (PB6, PB10, and PB11, respectively). The valve controls are interlocked such that the open circuit valve cannot be closed (blocking the tunnel flow circuit) unless the fill and exhaust valves are both open.

3.4 UTILITIES

Utility requirements for this facility are listed below.

Electric Motors

1 - 50 HP, 220V, 3ϕ, 60H_z, electric motor
1 - 200KW, " " " resistance heater
1 - 1.5 HP " " " electric motor
1 - 1.0 HP " " " " "
8 - fractional HP, 110V, 1ϕ electric motors

Compressed Air

60 scfm @ 125 psig

Tap Water

30 gpm @ 90 psig

Steam

76 lb/hr @ 15 psig

Fuel Oil

15 gpm of #2 distillate fuel oil

Natural Gas

2500 scfh @ 2 psig

Chilled Water

36 gpm @ 45°F

3.5 OTHER DESIGN DETAILS

Other features of the wind tunnel design include access hatches and drains for tunnel maintenance and cleanout, tunnel insulation, a laboratory housing, effluent requirements, and air exchange rates. These items are discussed below.

3.5.1 Cleanout

Tunnel cleanout is accomplished with a vacuum cleaner in heavily dust-laden areas, followed by hosing down and scrubbing with water. Access to the various parts of the wind tunnel for maintenance and cleanout is indicated in Figure 35 and described below.

1. Blower to air conditioner, 6' x 6' rectangular duct: hatchway in side of duct on both sides of open-circuit valve.
2. Gas conditioning section, 6' x 6' x 1' section: can be lifted out for major work or accessible from either side by means of hatches in adjacent duct sections.
3. Gas conditioner to turning vanes, 6' x 6' rectangular duct: hatchway in side of duct.
4. Turning vanes to settling section, 6' x 6' rectangular duct: hatchway in side of duct.
5. Settling section (honeycomb, screen and nozzle assembly): can be lifted out for major cleaning, or screens and honeycomb removable through upstream hatch. Access from other side by crawling through converging section.
6. Converging section: remove test section segment and crawl through 2-foot diameter opening, or remove screens and clean from upstream side.
7. Test sections: all removable and mounted on carts.
8. Turning section: accessible when adjacent test section is removed.

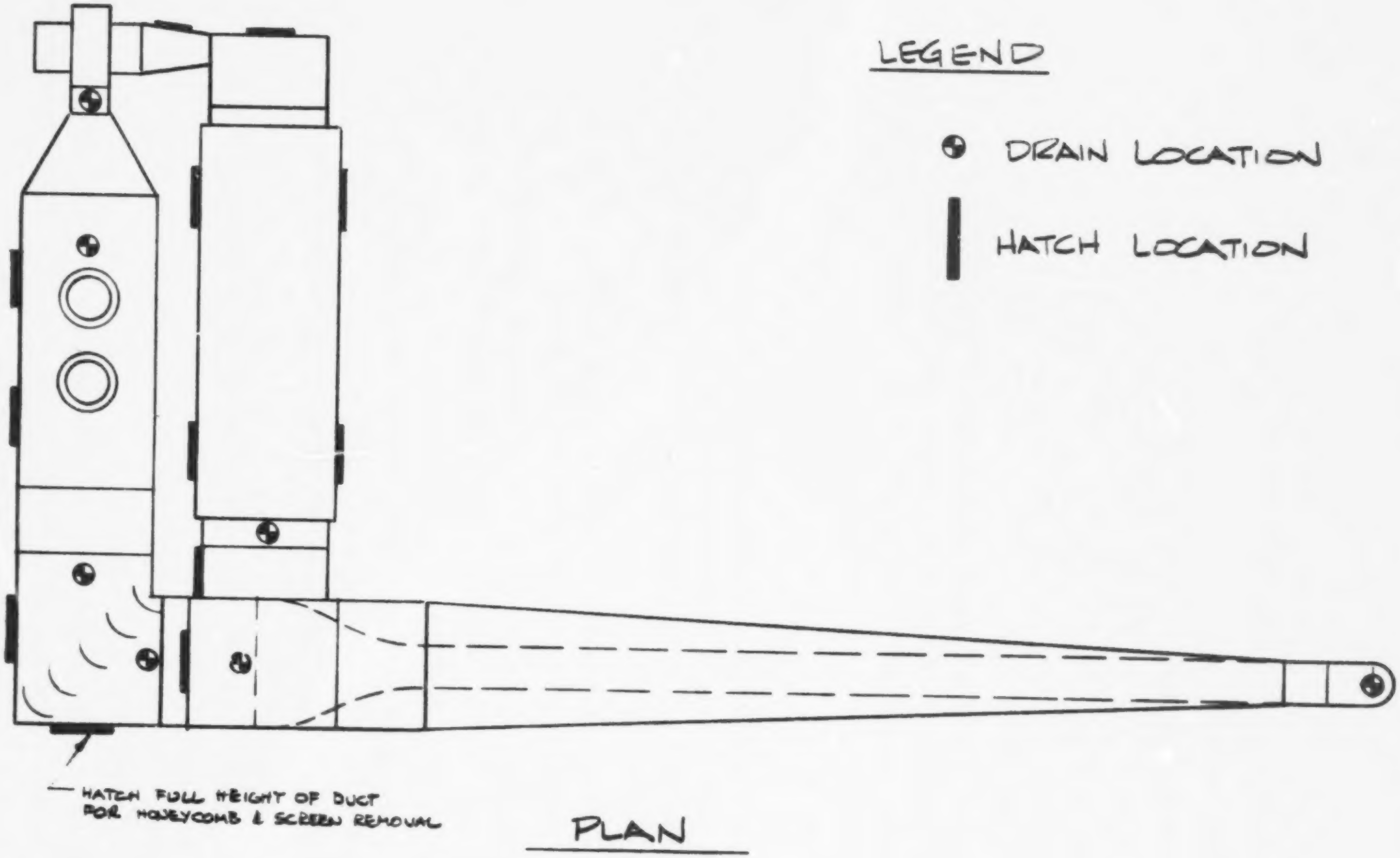

LEGEND
● DRAIN LOCATION
▮ HATCH LOCATION
HATCH FULL HEIGHT OF DUCT FOR HONEYCOMB & SCREEN REMOVAL
PLAN

FIGURE 35. ACCESS HATCHES AND DRAIN LOCATIONS.

9. Diffuser: hatchway at large end of diffuser.
10. Inlet to baghouse from diffuser: hatchway on side of 6' x 6' sloping rectangular duct.
11. Baghouse: hopper with screw fed dust ejector; hatches in both sides of baghouse for bag repair. Catwalks inside.
12. Baghouse to blower duct: hatch on top end of duct and on lower horizontal section before entering blower.
13. Blower: hatchway in housing.

Water from scrub-down operations or condensation will be drained from large drain couplings, shown in Figure 35, through large diameter hoses. Elevated hatchways and important locations, e.g., end of diffuser and top of baghouse will be accessible by means of ladders; permanently mounted if desired. All material gages are heavy enough to support ordinary foot traffic without damaging the tunnel surface.

3.5.2 Insulation

All surfaces of the tunnel circuit are insulated after tunnel installation (except the fan and baghouse which are insulated by the vendor). The material used is a semi-rigid spun-glass felt with a thickness of 2.0 inches. The insulation will be installed with metal bands, and covered with a canvas or other suitable flame resistant material.

3.5.3 Laboratory Housing

The test section and control console will be enclosed by a modular steel laboratory housing structure. The structure will include an ordinary door at either end and a 10'0" wide roll-up door at the center. The overall dimensions of this housing will 45'0" long by 15'0" wide, with an 8'0" ceiling. Space can be provided for storing instruments used with the tunnel, shelves, workbenches, and desks. This will be a prefabricated structure assembled after installation of the tunnel.

The laboratory housing is not shown in drawings M-1 or M-2 for clarity, however it is illustrated schematically in Figure 36.

3.5.4 Effluents

Durham County air pollution regulations[23] applying to this facility are as follows.

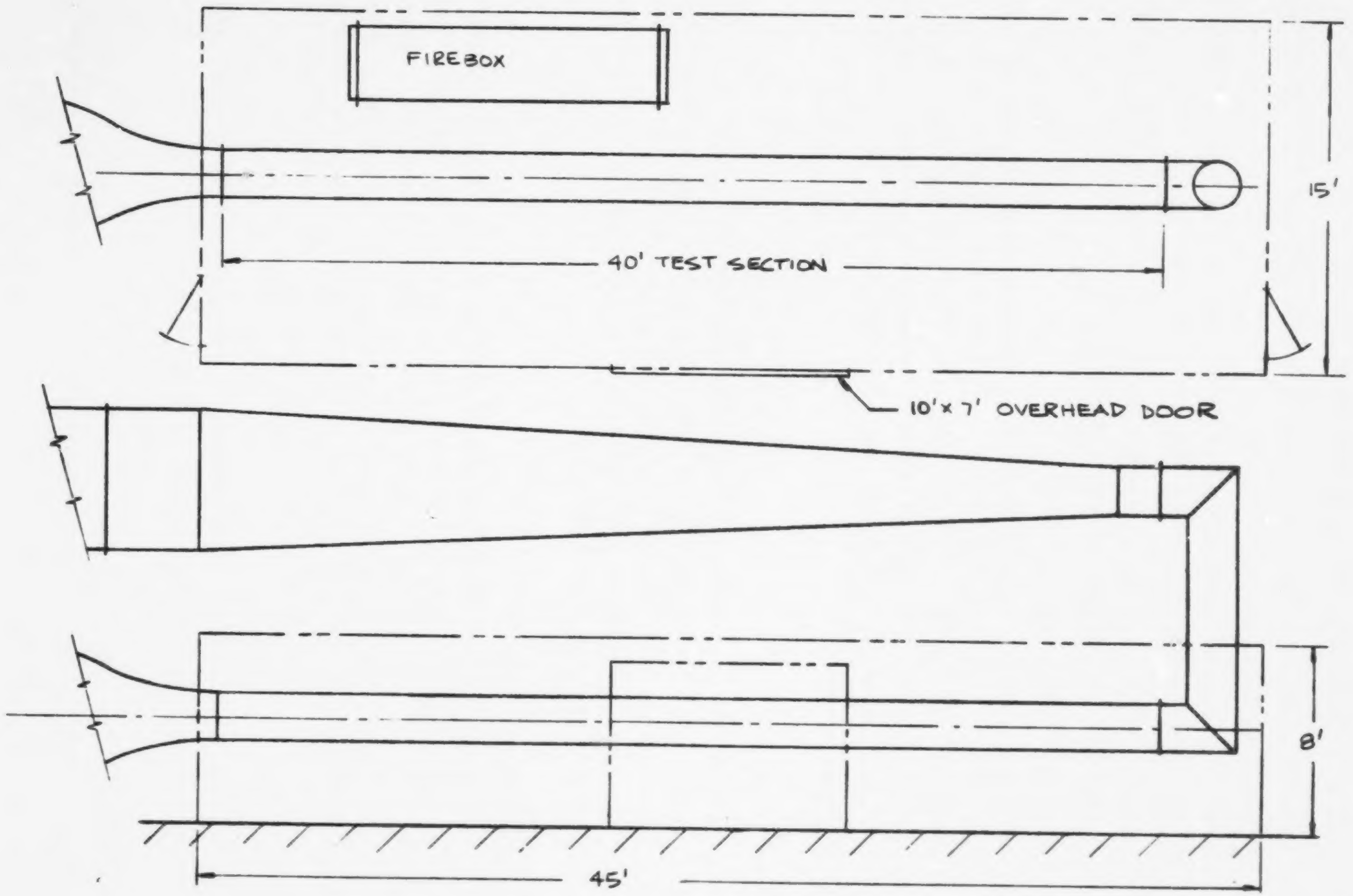

FIREBOX
15'
40' TEST SECTION
10'x 7' OVERHEAD DOOR
8'
45'

FIGURE 3G LABORATORY HOUSING

A-3946

Section 11.b.(1) - Emissions of smoke to the atmosphere must not exceed Ringlemann 1 for more than 4 minutes per hour, and not more than 20 minutes in any 24 hour period. Since particulate material is removed from the stream by the baghouse before exhausting to atmosphere, emissions are not expected to exceed this limitation.

Section 11.b.(7) - Flyash emissions must be less than 0.6 lbs/million Btu heat input. The baghouse will also satisfy this regulation.

Section 11.c.(1) - The lowest sulfur content fuel reasonably available shall be burned. Natural gas operation of the burner will not present a problem, and low sulfur fuel oil should be used.

Section 11.d. - Controllable particulate matter shall not be handled in such a manner as to cause it to become airborne. This rule should be followed during the course of facility operation.

Other city, state, and federal regulations are expected to be satisfied by the inclusion of the baghouse during open circuit operation, and by observation of the fuel selection and particulate handling procedures described above.

3.5.5 Air Exchange Requirements

All joints in the tunnel will be gasketed and made as leak tight as practical. If a leak occurs, e.g., from a misaligned duct or damaged gasket, it cannot be so substantial as to affect tunnel performance. We may assume that a leak equal to 10 percent of the tunnel flow would be noticeable and use this as a basis for estimating the air exchange requirements. The maximum tunnel flow is about 17,000 cfm, so two exhaust blowers, one in the laboratory housing around the test section and the other in the general laboratory area, of 1700 cfm capacity would continuously remove noxious gases.

SECTION 4

FACILITY CONSTRUCTION

The wind tunnel is divided into sections joined by bolting for ease in on-site assembly. Each section is small enough for truck shipment and can pass through the 10-foot wide entryways of the building. The baghouse will be delivered in broken down form and assembled at the site.

The control console will be wired as a unit with low voltage or low pressure signals fed to the various control points, e.g., motor speed, heater power, and valve actuators. Thus the compact, complex wiring of the console can be confined to the fabricator's workshop while the simpler cable runs can be prepared on site.

Due to the complexity and costs associated with construction of this facility, it is recommended that construction take place in phases. The phased construction and approximate costs are described below. Labor costs are typical loaded costs, while hardware costs are costs to the prime contractor.

Phase I: Detailed Design and Bid Package

Some revision in the design presented herein will be necessary, and final design drawings must be prepared. Incorporating changes, checking all drawings and component specifications, preparing bid packages, i.e., specifications and interface information, will require the following effort and associated (approximate) costs:

Engineering	$10,500
Drafting	3,500
Secretarial	1,000
	$15,000

Phase II: Construction of Elementary Wing Tunnel

The elementary wind tunnel would consist of:

1.	All ducting for closed circuit operation & supports, including one test section cart.	$35,000
2.	Baghouse, full capacity required, stainless steel where required	24,000
3.	Blower, motor & speed control (manual input)	4,500
4.	Windows (eight) in two short, 5-foot test sections	2,000
5.	Dust injector (borrowed hopper from EPA)	2,500
		$68,000

The cost of shipping, installing, and startup of the tunnel would breakdown as follows:

1.	Shipping	5,000
2.	Engineering	23,000
3.	Travel & living costs	3,500
4.	Riggers, local contractors	2,500
5.	Miscellaneous	8,000
		$42,000

With this equipment, the aerodynamic performance of the tunnel itself could be explored. The dust injection technique would be established. The low costs are accomplished by deleting many of the tunnel systems which are part of the final test facility. These deleted systems and components and approximate costs are:

1.	Inlet & exhaust valves (space provided but openings capped)	1,000
2.	Valve and ducts controlling dilution air to gas generator	600
3.	Open-circuit valve in large square duct	700
4.	Ducting to outside	1,500
5.	Valve in diffuser, from burner	900
6.	Gas generator & ducting, inlet & outlet	5,900
7.	Control console & permanent installations of thermocouples, velocity sensors, interlock switches, valve control relays	14,000
8.	Insulation	2,500
9.	Chilled water coil, humidifiers, & control	12,000
10.	Heater & control	7,000
11.	Laboratory housing	4,500
12.	Vibrating hopper, screw feeder & screws	6,000
13.	Test section carts (four)	1,500
		$57,400

The total cost of the elementary tunnel would be about $114,500. If we add the Phase I costs, the wind tunnel at the end of Phase II would cost $125,000.

Phase III: Permanent Installation and Additional Capabilities

During Phase II, all instrumentation was of a temporary nature, speed control was manual, and tunnel temperature was not controllable (limited to 150°-200°F steady state temperature). In Phase III, the following components would be added:

1.	Control console, permanent sensors (includes engineering & fabrication)	14,000
2.	Inlet & exhaust valves	1,000
3.	Open-circuit valve	700
4.	Exhaust duct	1,500
5.	Heater & control	7,000
6.	Air conditioning	12,000
7.	Insulation	2,500
8.	Dust feeder, bin, screws	6,000
9.	Test section carts (four)	1,500
		$46,200

Phase III engineering, installation and checkout cost would be:

1.	Engineering	20,000
2.	Travel & living costs	3,500
3.	Local contractors	2,500
4.	Miscellaneous	5,000
		$31,000

The total cost for Phase III would be $77,200.

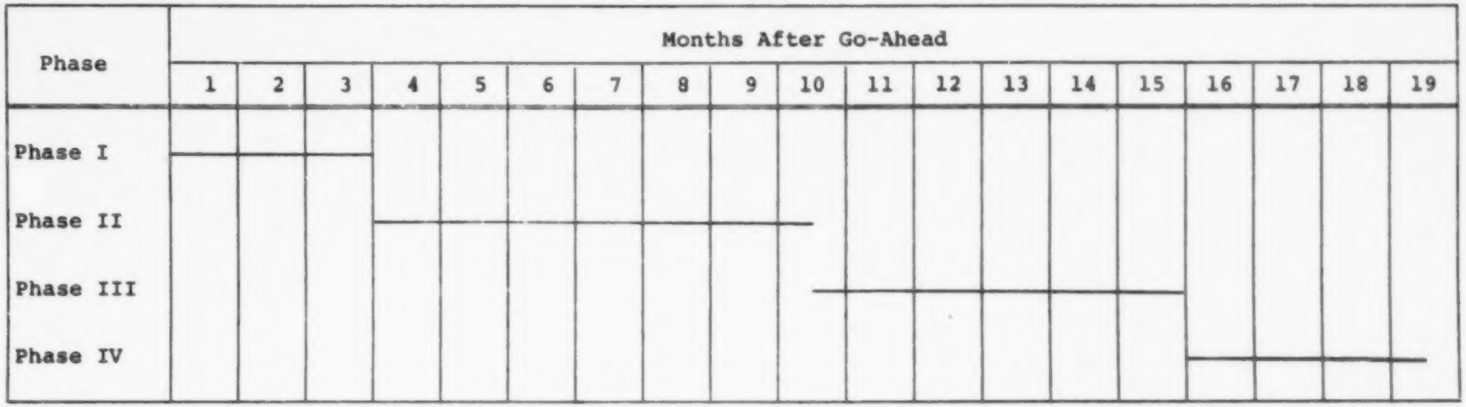
Phase IV: Completion of Facility

The wind tunnel facility would be completed during this phase which involves:

1.	Adding burner, firebox & ducting	5,900
2.	Exit valve from firebox	900
3.	Inlet air valve to firebox	600
4.	Laboratory housing	4,500
5.	Windows (12) in the 10-foot section	7,200
6.	Miscellaneous	8,000
		$27,100

Engineering, installation, and checkout costs would be about the same as in Phase III, which is $31,000. The total costs for Phase IV would be about $58,100. At this point, the facility is complete, checked out, and ready for use. The costs for Phase I, II, III, IV together amount to $260,300. A schedule for all four phases is shown on the next page. The entire job can be completed in two years.

SCHEDULE


Phase
Months After Go-Ahead
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Phase I
Phase II
Phase III
Phase IV

SECTION 5

SPECIFICATIONS

Specifications for each major component of the wind tunnel facility, along with three vendors (where possible), are given in Table 9.

TABLE 9

EQUIPMENT SPECIFICATIONS

Item	Qty.	Description	Vendors
1	1	Airfoil blade, centrifugal blower, insulated housing, 304 stainless steel construction on all airstream surfaces, flanged inlet and outlet, insulated inspection door, insulated drain connection. Working conditions: 16,700 CFM; 12" S.P.; 40 BHP - at 70°F, sea level 16,700 CFM; 7" S.P.; 24 BHP - at 450°F, sea level	1. Garden City Fan and Blower Co., 1701 Terminal Rd. Niles, Mich. 49120 2. H.K. Porter Co. 6900 E. Elm St. Los Angeles, Cal. 90022 3. Reese Blowpipe Co. 2929 5th Ave. Berkeley, Cal.
2	1	Constant speed, squirrel cage a.c. motor integral with eddy current drive unit. Horizontal foot mountings, blower cooled, continuous duty. Motor rating: 50 HP @ 1800 RPM, 230V, 3ϕ power Output speed range: 1715 - 50 RPM @ full rated torque	1. Eaton, Yale, and Towne Dynamatic Division 3122 - 14th Ave. Kenosha, Wisconsin 53140 2. U. S. Electrical Motors 1660 Rollins Rd. Burlingame, Cal. 3. Allis Chalmers Mfg. Co. Box 512 Milwaukee, Wis.
3	1	Silicon - controlled rectifier (SCR) - type solid state controller for item 2. Wall mounted, ventilated enclosure. Equipment furnished loose for mounting on control console includes: 1) run speed potentiometer, knob, and dial 2) run pushbutton 3) stop pushbutton	Same as Item 2.
4	3	Butterfly valves Light weight valves required for installation with bulb flanges in 1/8" thick steel ducting. Bubble-tight seal in closed position desirable. Electric motor or pneumatic actuator. Maximum operating temperature approx. 450°F. Maximum pressure in closed position, 10" of water. Exposed to flue gas. 2 valves @ 2' dia.; 1 valve @ 1' dia.	1. Industrial Clean Air, Inc. 2929 Fifth St. Berkeley, Cal. 94710 2. N. J. Hatter & Co. (Continental Valve Rep.) P.O. Box 1391 San Mateo, Cal. 3. Garden City Fan & Blower Co. 1701 Terminal Rd. Niles, Michigan 49120
5	1	Shutter valve. To fit 6' x 6' duct. Installed with bulb flanges. The number of shutter sections used is not critical. Electric motor or pneumatic actuation. Valve must withstand 10" water pressure differential in fully closed position. Operating temperature approx. 450°F max., exposed to flue gas.	Same Vendors as Item 4
6	1	Air conditioner. Must fit within the 72" x 72" duct section and operate in conjunction with the duct heater (item 7). Air conditioner will consist of the following equipment Chilled water coil and pump - 36 GPM, 45°F water (plant supply) Dry steam humidifier nozzles and actuators - 761b/hr of 15 psig, plant steam Pneumatic control system - use 125 psig plant air	1. Thermal Mechanical 612 Taylor Avenue Sunnyvale, California 94086 2. Simonsen Air Conditioning 1124 Quesada Ave. San Francisco, Cal. 3. Climate Engineering Inc. 855 Cherry Lane San Carlos, Calif.

TABLE 9 (Continued)

7	1	Duct heater and stainless steel frame to fit in 72" x 72" duct. Maximum heater load is 200KW @ 230V, 3φ, 60Hz. Flow through heater is as follows: Max. flow: 280 ft^3/sec @ T = 70 - 450°F Min. flow: 16 ft^3/sec @ T = 70 - 500°F Heater elements to be sheathed in stainless steel.	1. Trent Inc. 201 Leverington Ave. Philadelphia, Pa. 19172 2. Montgomery Brothers, Inc. 1831 Bayshore Highway Burlingame, Cal. 3. Hill and Dietrick 1927 Fairway Dr. San Leandro, Calif.
8	1	Saturable core reactor, 225 KVA, 230V, 3φ, 60Hz input, 75 VDC control, to be use as control unit for item 7.	1. Burton Equipment Co. 16708 Parkside Ave. P.O. Box 96 Cerritos, Cal. 90701
9	1	Live bottom bin and cover, 50 cubic foot capacity, 304 stainless steel on all contact surfaces, 230 V, 3φ, 60Hz vibrator motor, 1.5 HP.	1. Vibra Screw Inc. 755 Union Blvd. Totowa, N. J. 07512
10	1	Baghouse duct collector, panel construction, 304 stainless steel on clean air side, trough hopper and supports with special extended inlet. Capacities and sizes as follows: Filter Area - 2036 ft^2 Air Temperature - up to 425°F Bag Material - Nomex, 16oz. felt or equal Insulation - 1" thick, all external surfaces Cleaning - reverse - jet air flow, 100 psig air Partical Removal - 8" rotary air lock with 1/2 HP motor, 9" screw conveyor with 1 HP motor Timer for bag cleaning frequency furnished separately for mounting on control console.	1. Slick Corporation Mikropul Division Chatham Road Summit, N. J. 07901
11	-	All duct work bellows, and connecting flanges	1. Krenz Engineering Ashby Ave and 6th Berkeley, Calif. 2. Hipp Welding Inc. 4233 Middlefield Road Palo Alto, Cal. 3. Rees Blow Pipe Co. 2929 - 5th Ave. Berkeley, Cal.
12	1	Burner, natural gas or light distillate fuel oil, low excess air rates possible. Capacity is as follows: Oil - 15 GPH Gas - 2500 SCFH	1. S. T. Johnson Co. 940 Arlington Ave. Oakland, Cal. 2. Eclipse Fuel Engineering Combustion Division Rockford, Illinois 3. Pyronics Inc. Cleveland, Ohio
13	1	Burner control and safety interlock system, to be used for operation of item 12. Flame safeguard unit must include 1) flame-out detection and associated mandatory purge period after flame-out 2) trial-for-ignition period and associated transfer to flame-out detector	Same as Item 12

TABLE 9 (Continued)

		3) high or low ignition voltage interlock Other interlocks must include: 1) low tunnel velocity 2) firebox exhaust valve closed 3) insufficient dilution air 4) low combustion air pressure 5) high/low firebox pressure 6) low fuel pressure 7) high firebox temperature 8) high diffusor duct temperature	
14	1	Firebox, drawing M-19, super-duty firebrick or monolithic refractory, 10 or 12 gage steel jacketing.	1. Acurex Corporation Aerotherm Division 485 Clyde Ave. Mt. View, Cal. 94040
15	1	Velocity meter, to sense velocity in test section and control eddy current coupling (item 2). Features must include: 1) set-point indicator, ft/sec 2) ΔP sensors 3) temperature sensor 4) analog computer, to calculate actual velocity and generate error signal 5) velocity meter, indicating in ft/sec	1. Acurex Corporation Aerotherm Division 485 Clyde Ave. Mt. View, Cal. 94040
16	1	Control console (drawing M-20) for tunnel operation. Console contains on-off or open-close buttons for: 1) fan motor 2) cooling water pump 3) humidifiers 4) duct heater 5) dust feeder 6) burner blower 7) burner igniter 8) baghouse screw conveyor 9) baghouse rotating air-lock 10) tunnel inlet valve 11) tunnel exhaust valve 12) tunnel open circuit valve 13) dilution air valve 14) firebox exhaust valve Set point controllers must include 1) velocity in test section 2) temperature in test section 3) humidity in test section 4) baghouse reverse jet frequency Indicators or meters must be included for 1) test section velocity 2) temperature at seven locations 3) test section humidity 4) air pressure at three locations 5) facility steam pressure 6) facility water pressure 7) dilution air flow rate	1. Acurex Corporation Aerotherm Division 485 Clyde Ave. Mt. View, Cal. 94040

TABLE 9 (Concluded

		Fault lights indicating the condition of system interlocks must be included as follows: 1) Fan motor - motor cooling air blower not operating 2) Fan motor - fan not rotating 3) Fan motor - air temperature too high 4) Fan motor - open circuit valve closed, inlet and exhaust valves not open 5) Chilled water pump - no water flow 6) Humidifier - no steam flow 7) Duct heater - no air velocity through heater elements 8) Duct heater - element overheat 9) Baghouse - gas temperature too high 10) Burner - any one of a series of interlocks on the burner is not satisfied. Burner faults are listed under Item 13. The console also must include a writing shelf, the air pressure regulator for pneumatic insturments, and the duct heater controller.	
17	1	Prefabricated laboratory housing surrounding test section area. Approximate dimensions of 40' x 15' x 8', doors included at either end, with roll-up, 10' 0" wide door at center.	1. Stran-Steel Inc.

REFERENCES

1. Pope, A. and Harper, J. J., Low Speed Wind Tunnel Testing, John Wiley and Sons, Incorporated, New York, 1966.

2. Bradshaw, P., "A Low-Turbulence Wind Tunnel Driven by an Aerofoil-Type Centrifugal Blower," Journal of the Royal Aeronautical Society, Vol. 71, February 1967, pp. 132-134.

3. Johnson, G. A., et al., "Performance Characteristics of Centrifugal Scrubbers," Chemical Engineering Progress, Vol. 51, No. 4, April 1955, pp. 176-188.

4. Martin, J. R., Taylor, N. C., and Plumley, A. L., "The C-E Air Pollution Control Systems," Paper presented at 1970 Industrial Coal Conference, University of Kentucky, April 1970.

5. Trezak, G. J. and Soo, S. L., "Gas Dynamics of Accelerating Particulate Flow in Circular Ducts," Proceedings of the 1966 Heat Transfer and Fluid Mechanics Institute," M. A. Saad and J. A. Miller, editors, Stanford University Press, Stanford, California, 1966.

6. Byers, R. L. and Calvert, S., "Particle Deposition from Turbulent Streams by Means of Thermal Force," I and EC Fundamentals, Vol. 8, No. 4, November 1969.

7. Personal communication with Mr. R. F. Tanner, Lockheed-Georgia Research Laboratory, Marietta, Georgia, September 1971.

8. Lieberman, A., "Aerosol Rarefaction Studies," American Industrial Hygiene Association Journal, September-October 1968, pp. 444-449.

9. Sehmel, G. A. and Schwendiman, L. C., "Particle Deposition from Turbulent Air Flow," Battelle-Northwest, Richland, Washington, Annual Report for 1969 to the USAEC Division of Biology and Medicine, BNWL-1307, Part 1, UC-48, June 1970.

10. Snyder, W. H. and Lumley, J. L., "Some Measurements of Particle Velocity Autocorrelation Functions in a Turbulent Flow," unpublished report obtained from J. L. Lumley, Department of Aerospace Engineering, The Pennsylvania State University, University Park, Pennsylvania, January 1971.

11. Habibi, K., "Characterization of Particulate Lead in Vehicle Exhaust - Experimental Techniques," Environmental Science and Technology, Vol. 4, No. 3, March 1970, pp. 239-248.

12. Bulba, E. and Silverman, L., "A Recirculating Aerosol Tunnel," APCA Paper No. 66-82, June 1966.

13. Soo, S. L., et. al., "Concentration and Mass Flow Distributions in a Gas-Solid Suspension," I and EC Fundamentals, Vol. 3, No. 2, May 1964, pp. 98-106.

14. Personal communication with Mr. Murrell Selden, Walter C. McCrone Associates, Inc., Chicago, Illinois, March 1971.

15. Anon., Steam, Its Generation and Use, The Babcock and Wilcox Company, New York, 1955.

16. Personal communication with Mr. A. Lieberman, Royco Instrument Company, Menlo Park, California, January 1971.

17. Hinze, J. O., Turbulence, McGraw-Hill Book Company, Inc., New York, 1959.

18. Pankhurst, R. C. and Holder, D. W., Wind Tunnel Techniques, Sir Isaac Pitman and Sons, Ltd., London, 1952.

19. Bradshaw, P. and Pankhurst, R. C., "The Design of Low Speed Wind Tunnels," in Progress in Aeronautical Sciences, Vol. 5, D. Kuchemann and L. Sterne, editors, Oxford, Pergammon Press, Ltd., New York, MacMillan Company, 1964, pp. 1-67.

20. Becker, H. A., Rosensweig, R. E., and Gwozdz, J. R., "Turbulent Dispersion in a Pipe Flow,: AICHE Journal, Vol. 12, No. 5, September 1966.

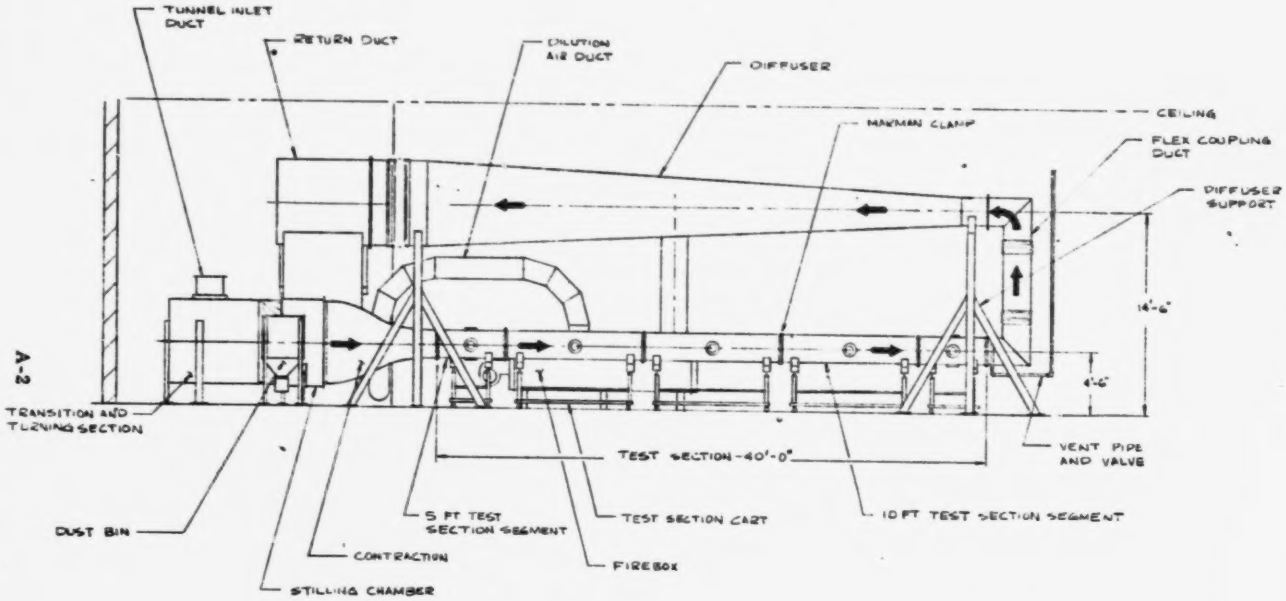
21. Bradshaw, P., "Simple Wind Tunnel Design," National Physical Laboratory, Aerodynamics Division, NPL Aero Report 1258, February 1968.

22. Cohen, M. J. and Ritchie, N. J. B., "Low Speed Three-Dimensional Contraction Design," Journal of the Royal Aeronautical Society, Vol. 66, 1962, p. 231.

23. Anon., "An Ordinance Providing for the Conservation of Air Resources by Prevention, Abatement, and Control of Air Pollution," obtained from Mr. Copeland at Durham County Health Department, Durham, North Caroline, January 1971.

APPENDIX

Drawings M-1 through M-22 are included in this Appendix.


TUNNEL INLET DUCT
RETURN DUCT
DILUTION AIR DUCT
DIFFUSER
CEILING
MARMAN CLAMP
FLEX COUPLING DUCT
DIFFUSER SUPPORT
14'-6"
4'-6"
VENT PIPE AND VALVE
TEST SECTION-40'-0"
TRANSITION AND TURNING SECTION
DUST BIN
5 FT TEST SECTION SEGMENT
TEST SECTION CART
10 FT TEST SECTION SEGMENT
CONTRACTION
FIREBOX
STILLING CHAMBER

REVISIONS
LTR DESCRIPTION DATE APPROVED

-02 -01 ITEM NO PART NO MANUFACTURER DESCRIPTION
QTY REQD LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS DECIMALS ANGLES
ALL ✓ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN. TREAT
MATERIAL
FINISH

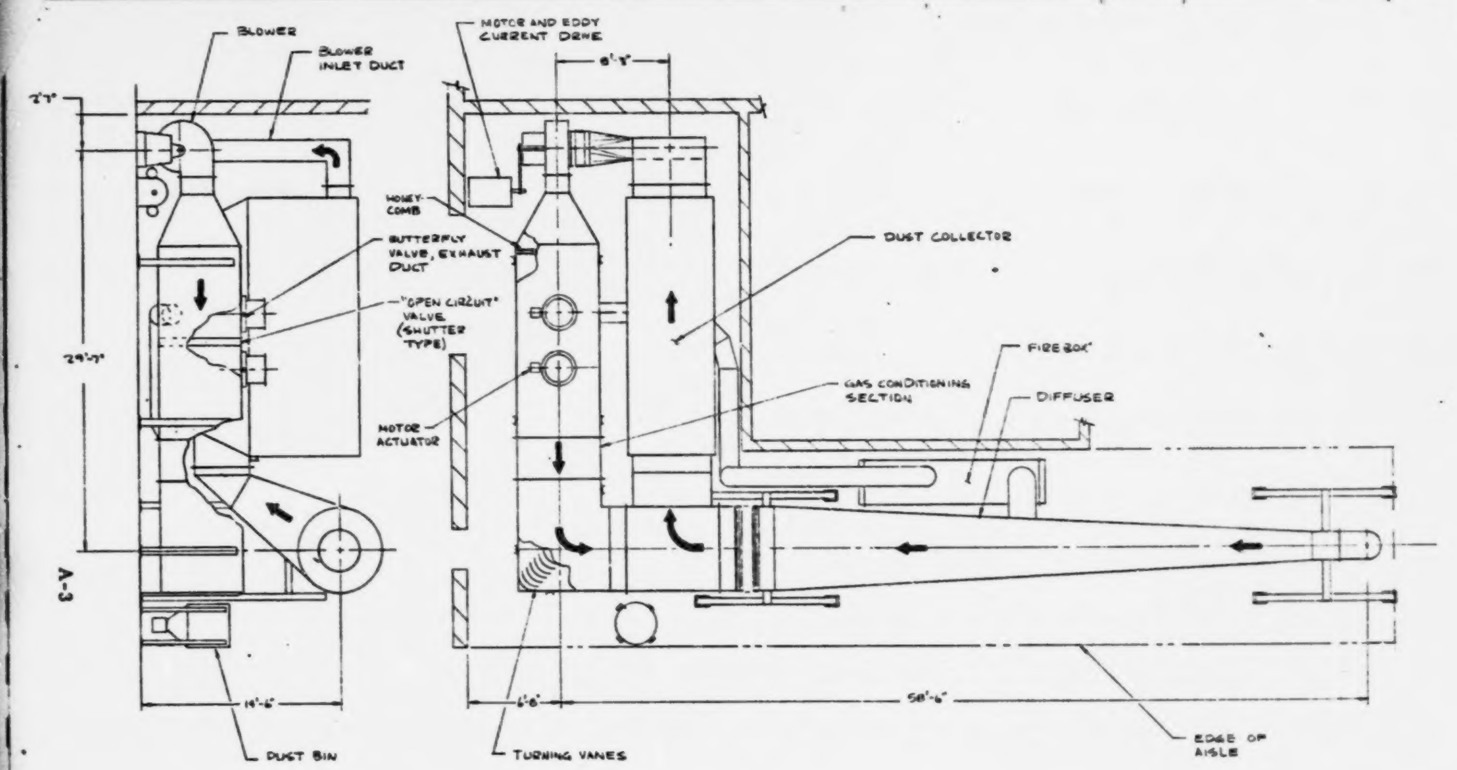
DRAWN Dull DATE
CHECKED
ENGINEER
APPROVED

AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94040

PARTICLE WIND TUNNEL
OUTLINE DRAWING

SIZE D CODE IDENT NO DRAWING NO 1A-1
SCALE SHEET 1 OF 1

NEXT ASSY QTY USED ON QTY
APPLICATION


BLOWER
BLOWER INLET DUCT
2'7"
29'-7"
HONEY-COMB
BUTTERFLY VALVE, EXHAUST DUCT
"OPEN CIRCUIT" VALVE (SHUTTER TYPE)
MOTOR ACTUATOR
14'-6"
DUST BIN
MOTOR AND EDDY CURRENT DRIVE
8'-3"
DUST COLLECTOR
GAS CONDITIONING SECTION
FIREBOX
DIFFUSER
6'-8"
58'-6"
TURNING VANES
EDGE OF AISLE

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED

-02	-01	ITEM NO	PART NO	MANUFACTURER	DESCRIPTION
QTY REQD			LIST OF MATERIALS		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES

DRAWN
CHECKED
ENGINEER
APPROVED

MATERIAL

FINISH

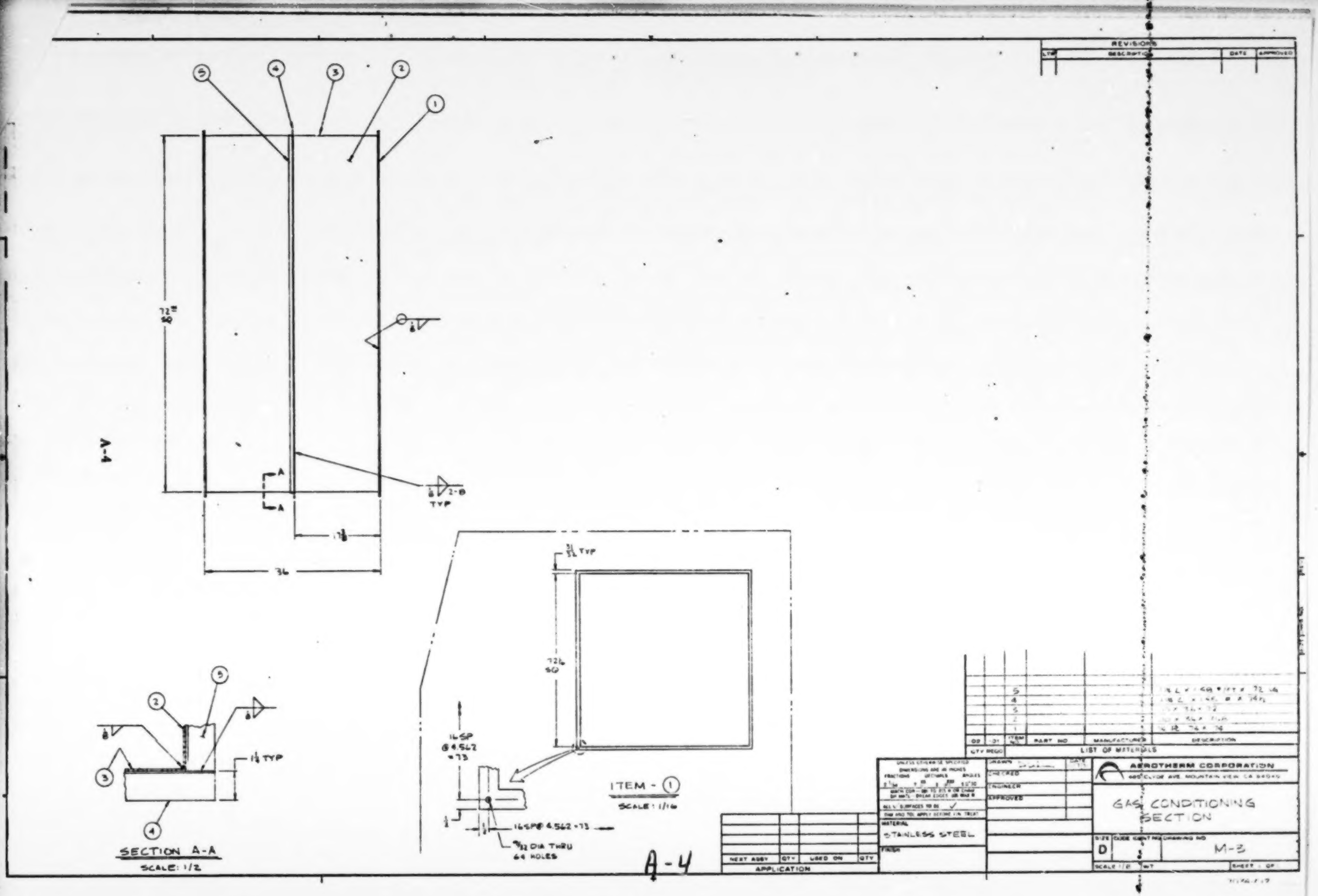
NEXT ASSY	QTY	USED ON	QTY

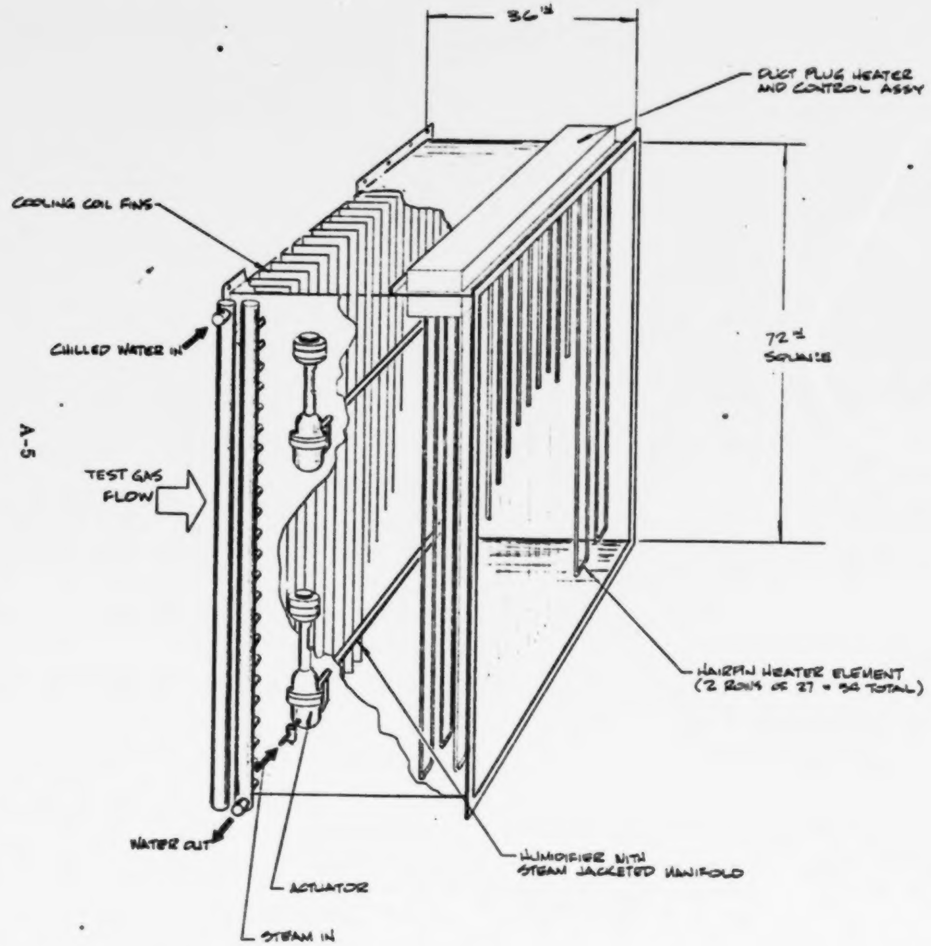
APPLICATION

AEROTHERM CORPORATION

PARTICLE WIND TUNNEL
OUTLINE DRAWING

SIZE D
DRAWING NO M-2
SCALE
SHEET 2 OF 2


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
①
②
③
④
⑤
72" SQ
36
1 7/8
1/8
1/8 2-8 TYP
A
A
3/16 TYP
72 1/4 SQ
16 SP @ 4.562 = 73
16 SP @ 4.562 = 73
9/32 DIA THRU 64 HOLES
ITEM - ①
SCALE: 1/16
SECTION A-A
SCALE: 1/2
1 1/4 TYP
A-4
NEXT ASSY
QTY
USED ON
QTY
APPLICATION
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS
DECIMALS
ANGLES
ALL SURFACES TO BE ✓
MATERIAL
STAINLESS STEEL
FINISH
DRAWN
CHECKED
ENGINEER
APPROVED
DATE
QTY REQD
ITEM NO
PART NO
MANUFACTURER
DESCRIPTION
LIST OF MATERIALS
5
4
3
2
1
AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94040
GAS CONDITIONING SECTION
SIZE
D
CODE IDENT NO
DRAWING NO
M-3
SCALE 1/8
WT
SHEET 1 OF


36"
DUCT PLUG HEATER AND CONTROL ASSY
COOLING COIL FINS
72" SQUARE
CHILLED WATER IN
TEST GAS FLOW
HAIRPIN HEATER ELEMENT (2 ROWS OF 27 = 54 TOTAL)
WATER OUT
ACTUATOR
HUMIDIFIER WITH STEAM JACKETED MANIFOLD
STEAM IN

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED

-02	-01	ITEM NO	PART NO	MANUFACTURER	DESCRIPTION
QTY REQD			. ST OF MAT . IALS		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS DECIMALS ANGLES
ALL ✓ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN TREAT
MATERIAL
FINISH

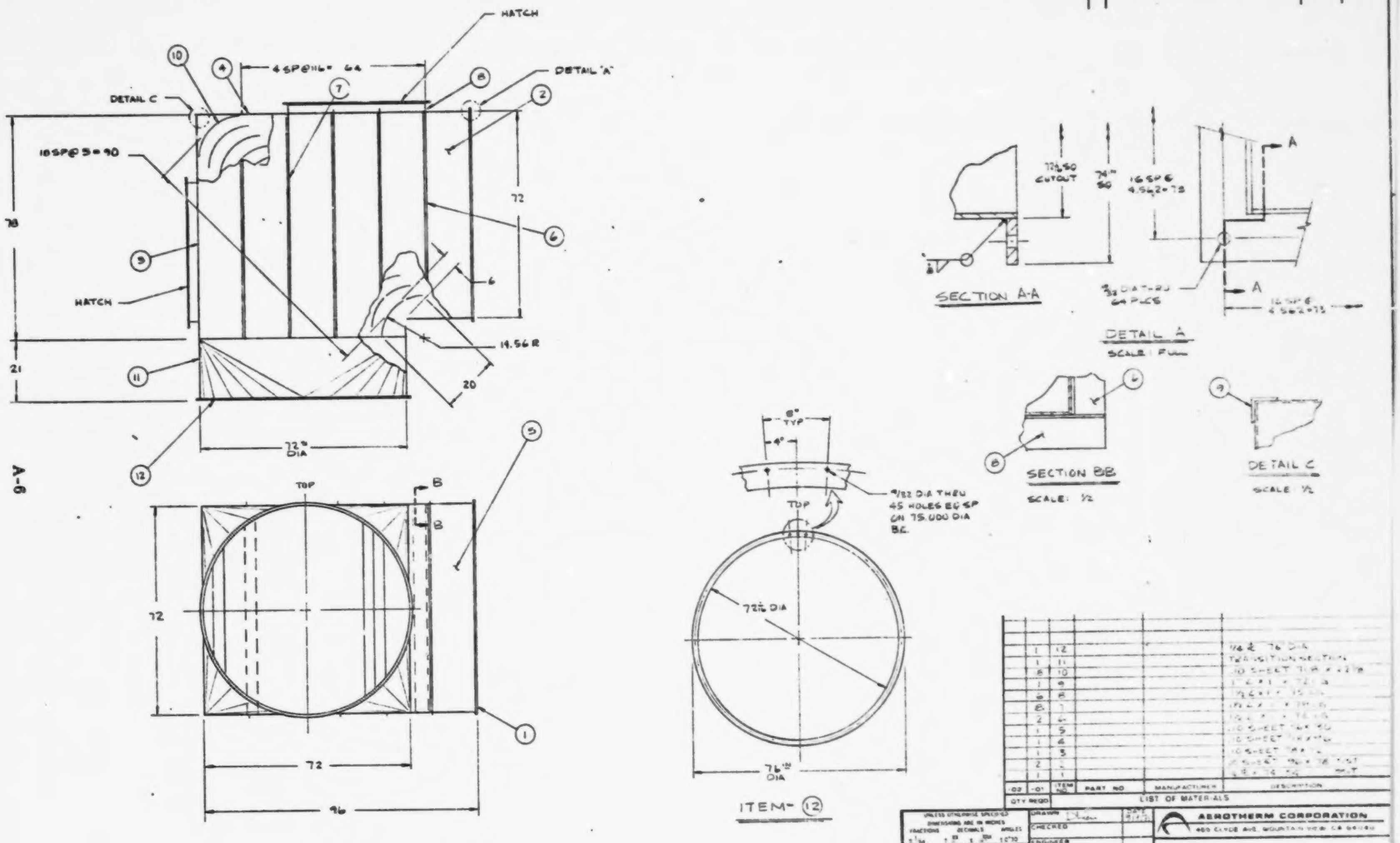
DRAWN
CHECKED
ENGINEER
APPROVED

AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94040

GAS CONDITIONING
SECTION OUTLINE DWG

SIZE D
CODE IDENT NO
DRAWING NO M-4
SCALE
WT
SHEET 1 OF 1

NEXT ASSY	QTY	USED ON	QTY
APPLICATION			



HATCH
DETAIL C
DETAIL 'A'
4 SP @ 16 = 64
18 SP @ 5 = 90
78
72
21
6
14.56 R
20
72" DIA
TOP
B
B
72
72
96
①
②
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫
A-6
SECTION A-A
72½ 50 CUTOUT
74" 50
16 SP @ 4.562 = 73
A
A
9/32 DIA THRU 64 PLCS
DETAIL A
SCALE: FULL
SECTION BB
SCALE: 1/2
DETAIL C
SCALE: 1/2
8" TYP
4"
TOP
9/32 DIA THRU 45 HOLES EQ SP ON 75.000 DIA B.C.
72⅞ DIA
76 1/8" DIA
ITEM- ⑫

-02	-01	ITEM NO.	PART NO	MANUFACTURER	DESCRIPTION
	1	12			1/4 ℄ 76 DIA
	1	11			TRANSITION SECTION
	8	10			.10 SHEET [illegible]
	1	9			[illegible]
	6	8			[illegible]
	8	7			[illegible]
	2	6			[illegible]
	1	5			.10 SHEET [illegible]
	1	4			.10 SHEET [illegible]
	1	3			.10 SHEET [illegible]
	2	2			.10 SHEET 96 x 78 [illegible]
	1	1			[illegible] x 76 [illegible]

QTY REQD — LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

MATERIAL: 304 STAINLESS

DRAWN: Dl[illegible]

AEROTHERM CORPORATION

485 CLYDE AVE. MOUNTAIN VIEW, CA 94040

TURNING AND
TRANSITION SECTION

SIZE D — DRAWING NO. M-5

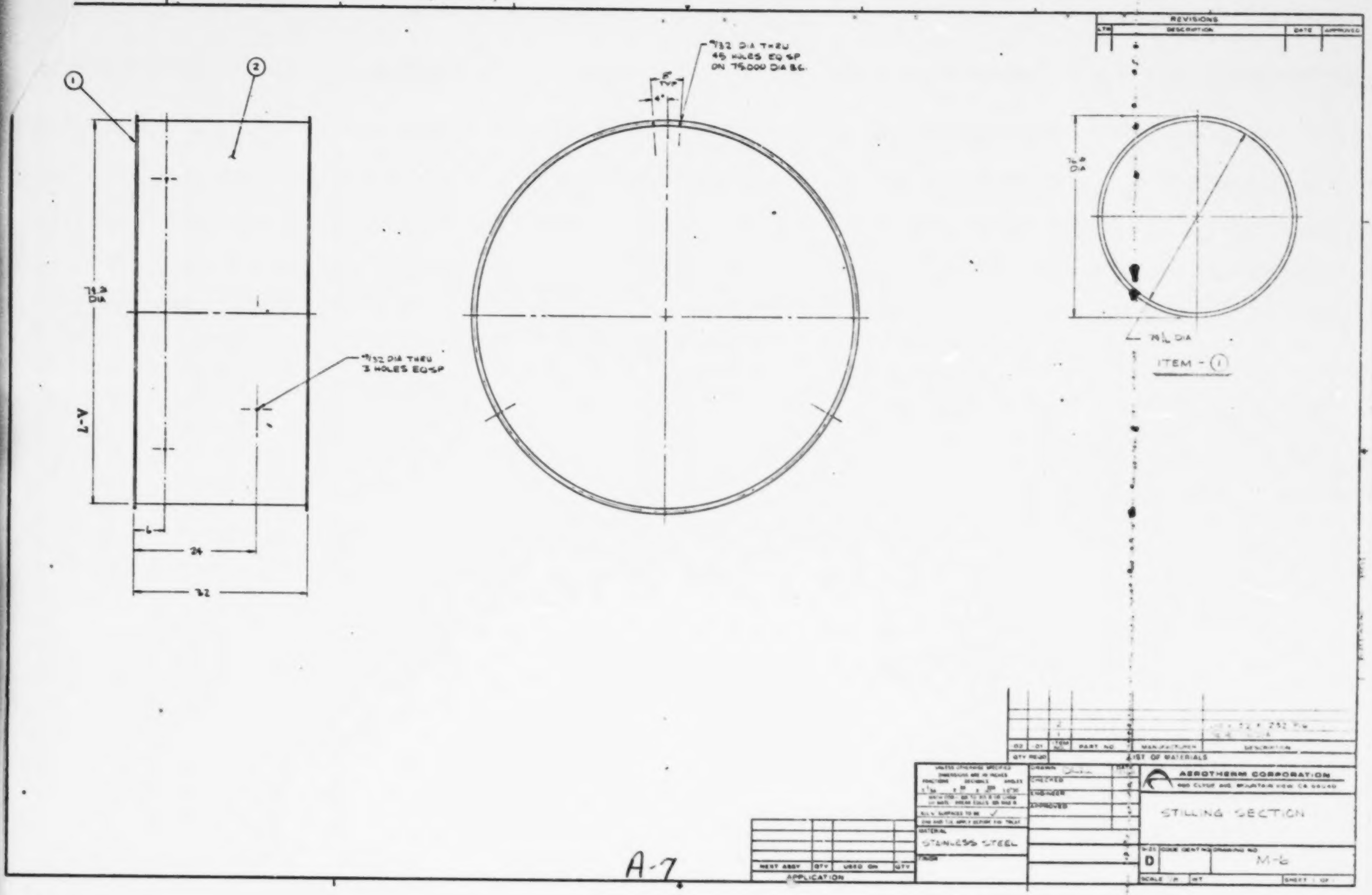
SCALE 1/4" — SHEET 1 OF 1

1059 007

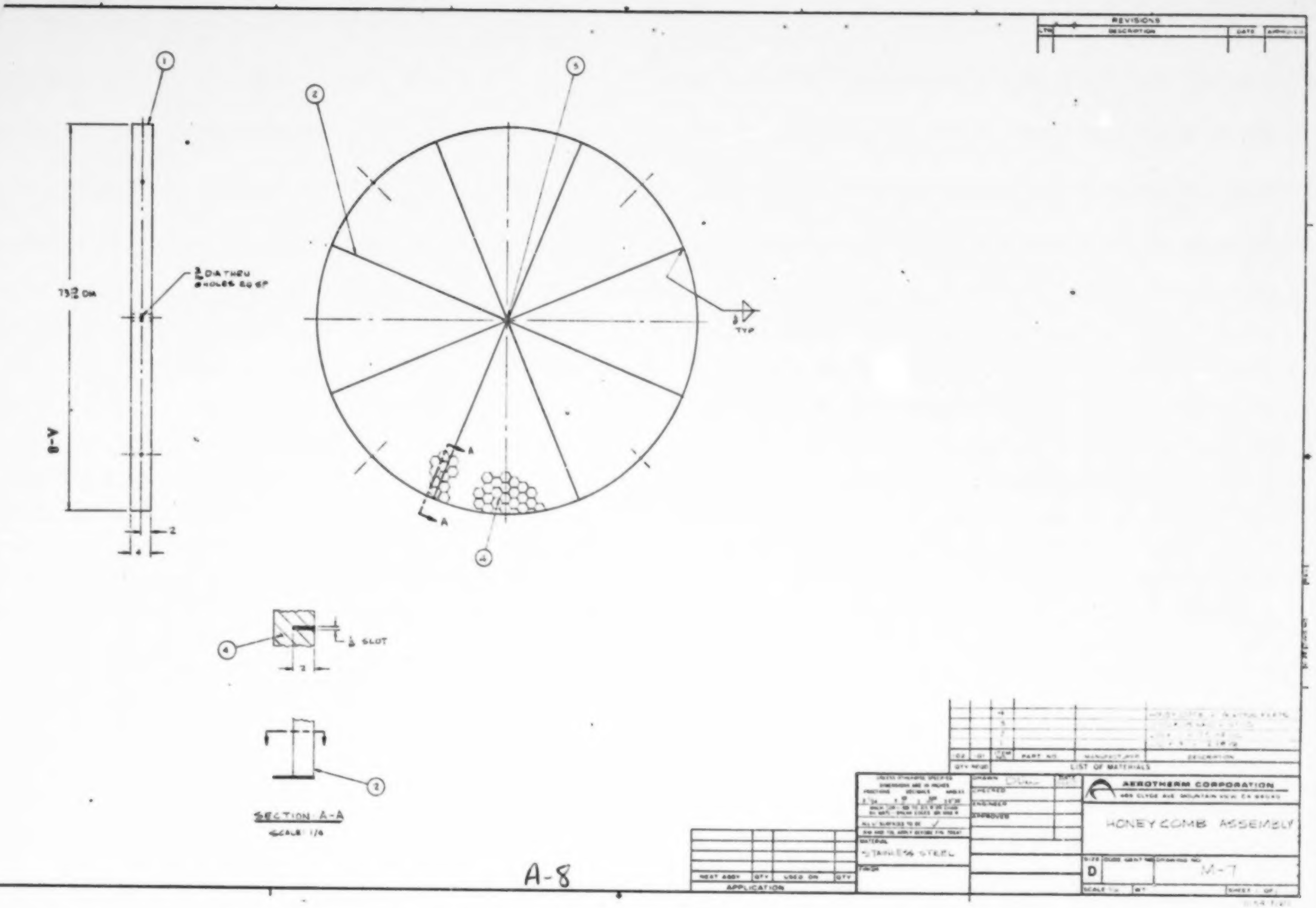
NEXT ASSY | QTY | USED ON | QTY — APPLICATION

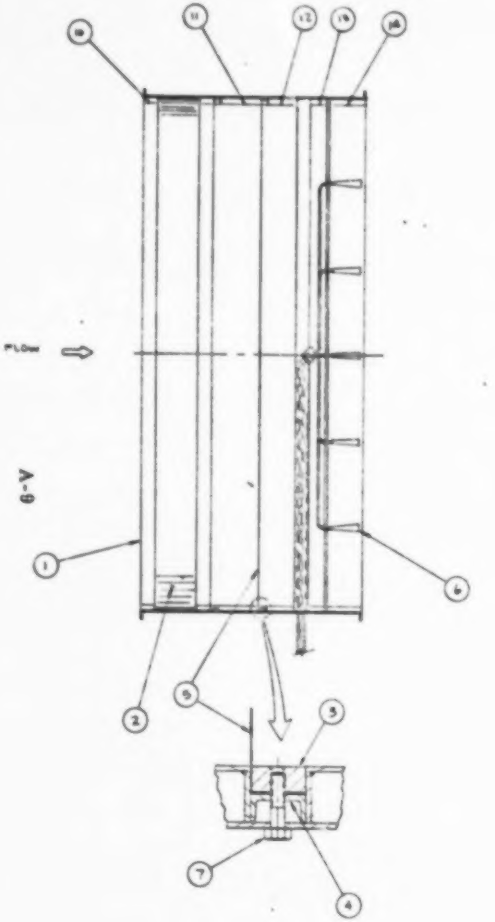
REVISIONS: LTR | DESCRIPTION | DATE | APPROVED

A-6

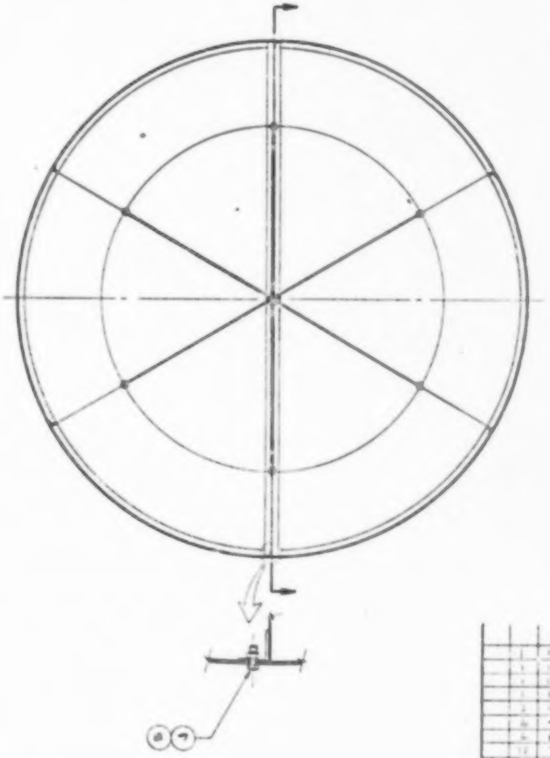
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
①
②
79.3 DIA
A-7
6
24
32
9/32 DIA THRU
3 HOLES EQ SP
9/32 DIA THRU
45 HOLES EQ SP
ON 75.000 DIA B.C.
8° TYP
4°
76.8 DIA
78 1/16 DIA
ITEM - ①
2
1
QTY REQD
-02
-01
ITEM NO
PART NO
MANUFACTURER
DESCRIPTION
LIST OF MATERIALS
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ALL SURFACES TO BE ✓
MATERIAL
STAINLESS STEEL
FINISH
DRAWN
CHECKED
ENGINEER
APPROVED
DATE
AEROTHERM CORPORATION
460 CLYDE AVE. MOUNTAIN VIEW, CA 94040
STILLING SECTION
SIZE
D
CODE IDENT NO
DRAWING NO
M-6
SCALE
WT
SHEET 1 OF 1
NEXT ASSY
QTY
USED ON
QTY
APPLICATION

A-7


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
①
②
⑤
④
73½ DIA
⅜ DIA THRU
8 HOLES EQ SP
A-8
2
4
⅛
TYP
A
A
½ SLOT
SECTION A-A
SCALE: 1/6
QTY REQD
PART NO
MANUFACTURER
DESCRIPTION
LIST OF MATERIALS
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
DRAWN
CHECKED
ENGINEER
APPROVED
MATERIAL
STAINLESS STEEL
FINISH
NEXT ASSY
QTY
USED ON
QTY
APPLICATION
AEROTHERM CORPORATION
485 CLYDE AVE MOUNTAIN VIEW CA 94040
HONEYCOMB ASSEMBLY
SIZE
D
DRAWING NO
M-7
SCALE
WT
SHEET 1 OF 1



A-9



REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED

-02	-01	ITEM NO	PART NO	MANUFACTURER	DESCRIPTION
	1	14			SPACER
	1	13			SPACER
	1	12			SPACER
	1	11			SPACER
	1	10			SPACER
	6	9			HEX NUT [illegible]
	6	8			BOLT [illegible]
	12	7			BOLT [illegible]
	1	6	10134-[illegible]		[illegible] ASSEMBLY
	2	5			SCREEN
	2	4	10134-[illegible]		OUTER SCREEN [illegible]
	2	3	[illegible]		[illegible] SCREEN [illegible]
	1	2	[illegible]		HONEYCOMBED [illegible]
	1	1	10134-[illegible]		STILLING SECTION
QTY REQD		LIST OF MATERIALS			

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS DECIMALS ANGLES
ALL SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN TREAT
MATERIAL
FINISH

DRAWN DATE
CHECKED
ENGINEER
APPROVED

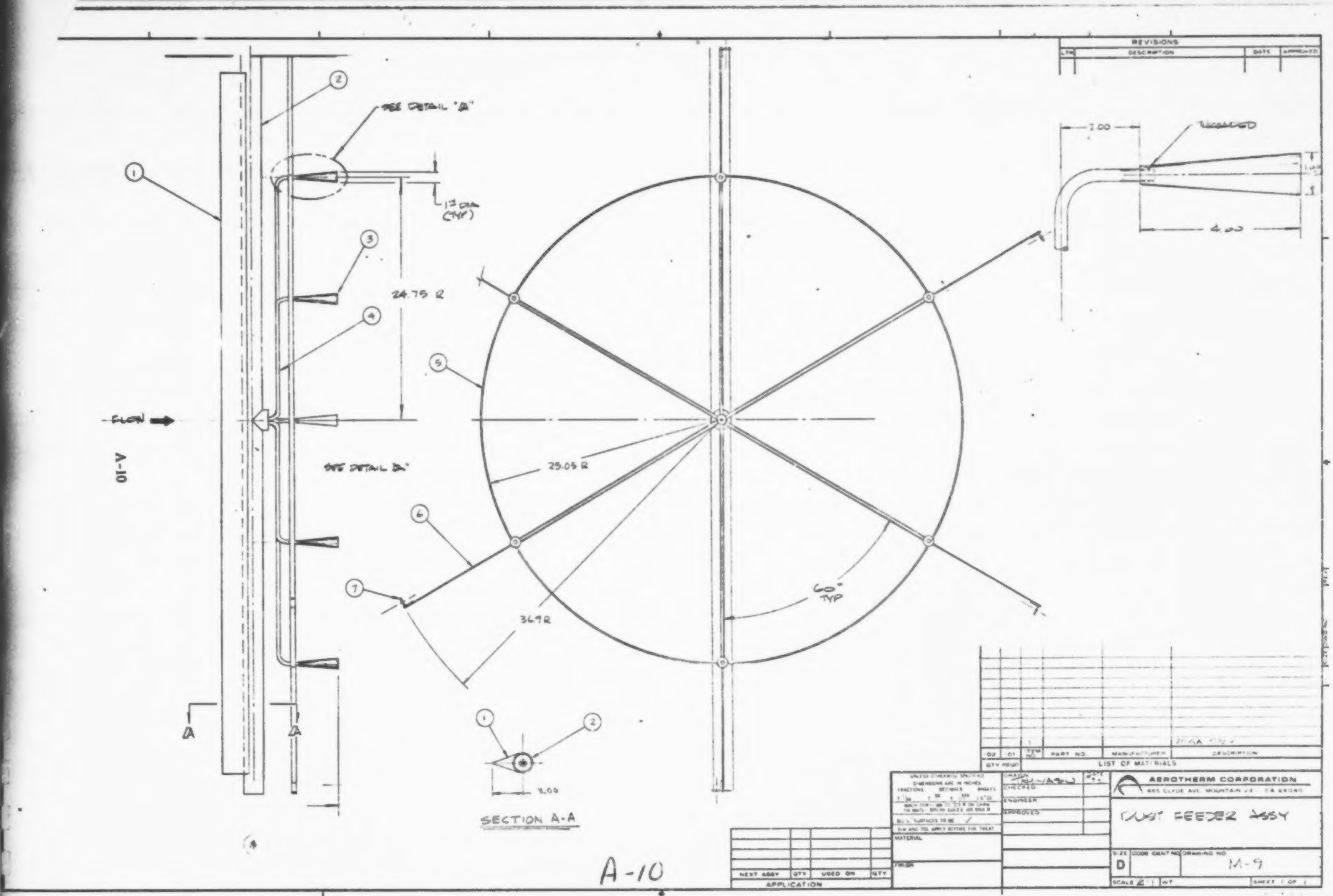
AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW CA 94040

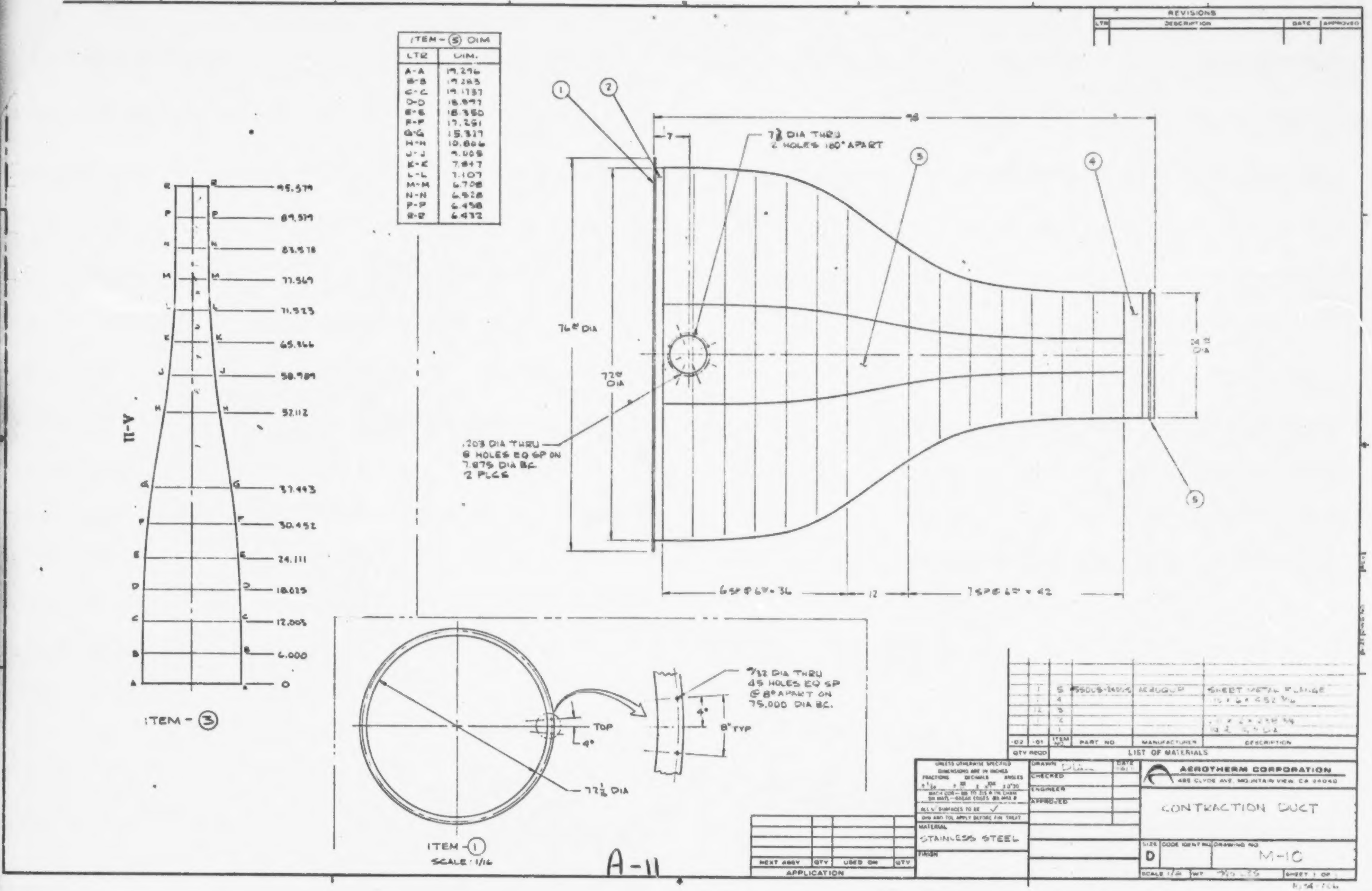
STILLING CHAMBER
ASSEMBLY

SIZE D
CODE IDENT NO
DRAWING NO M-8
SCALE
WT
SHEET 1 OF 1

NEXT ASSY	QTY	USED ON	QTY
APPLICATION			

A-9

REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
2.00
THREADED
4.00
1.00
SEE DETAIL "A"
1" DIA (TYP)
24.75 R
SEE DETAIL "A"
FLOW
25.05 R
36.9 R
60° TYP
①
②
③
④
⑤
⑥
⑦
A
A
3.00
SECTION A-A
QTY REQD
ITEM NO.
PART NO.
MANUFACTURER
DESCRIPTION
LIST OF MATERIALS
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
FRACTIONS
DECIMALS
ANGLES
MATERIAL
FINISH
DRAWN
DATE
CHECKED
ENGINEER
APPROVED
AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94040
DUST FEEDER ASSY
SIZE
D
CODE IDENT NO
DRAWING NO
M-9
SCALE
WT
SHEET 1 OF 1
NEXT ASSY
QTY
USED ON
QTY
APPLICATION

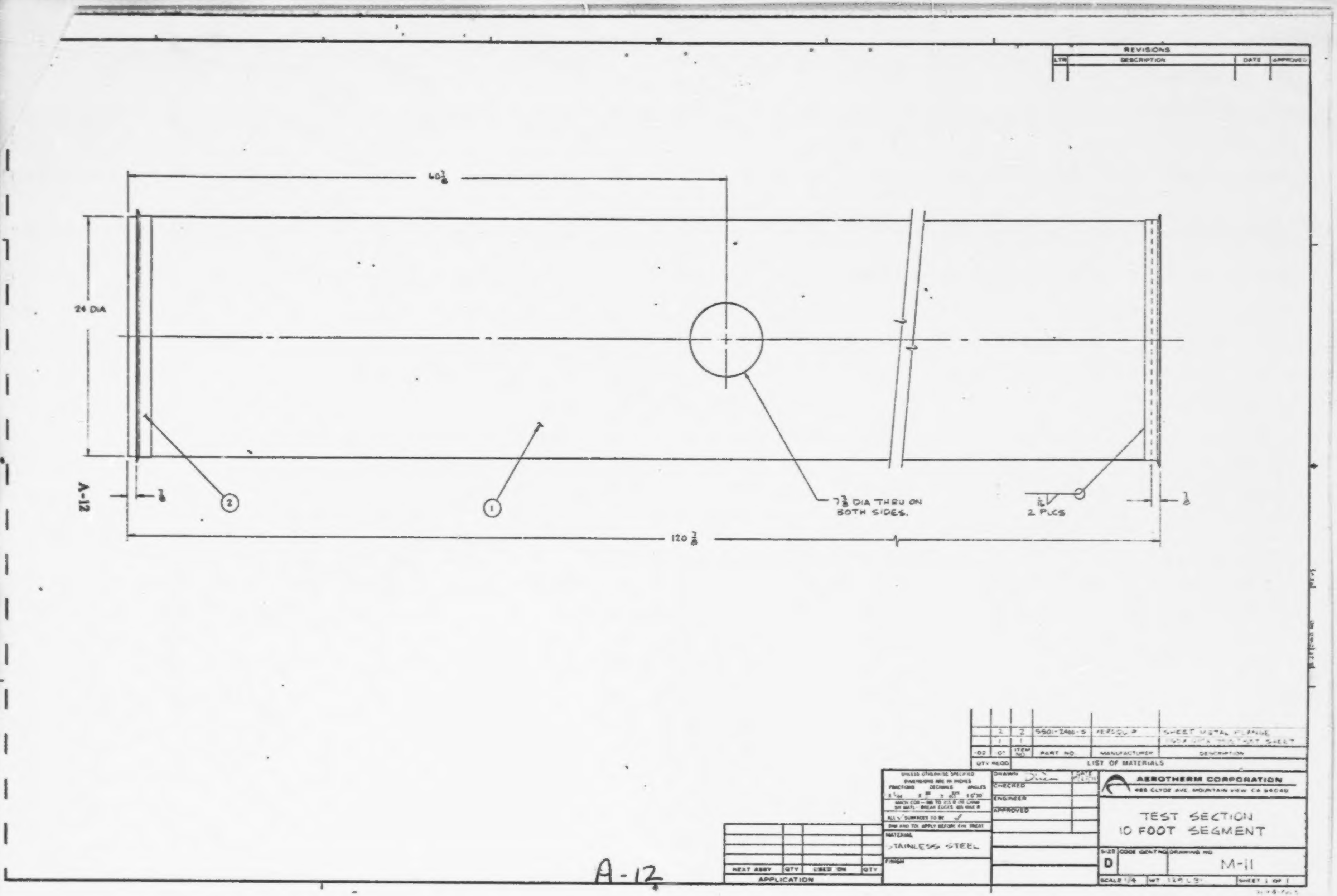


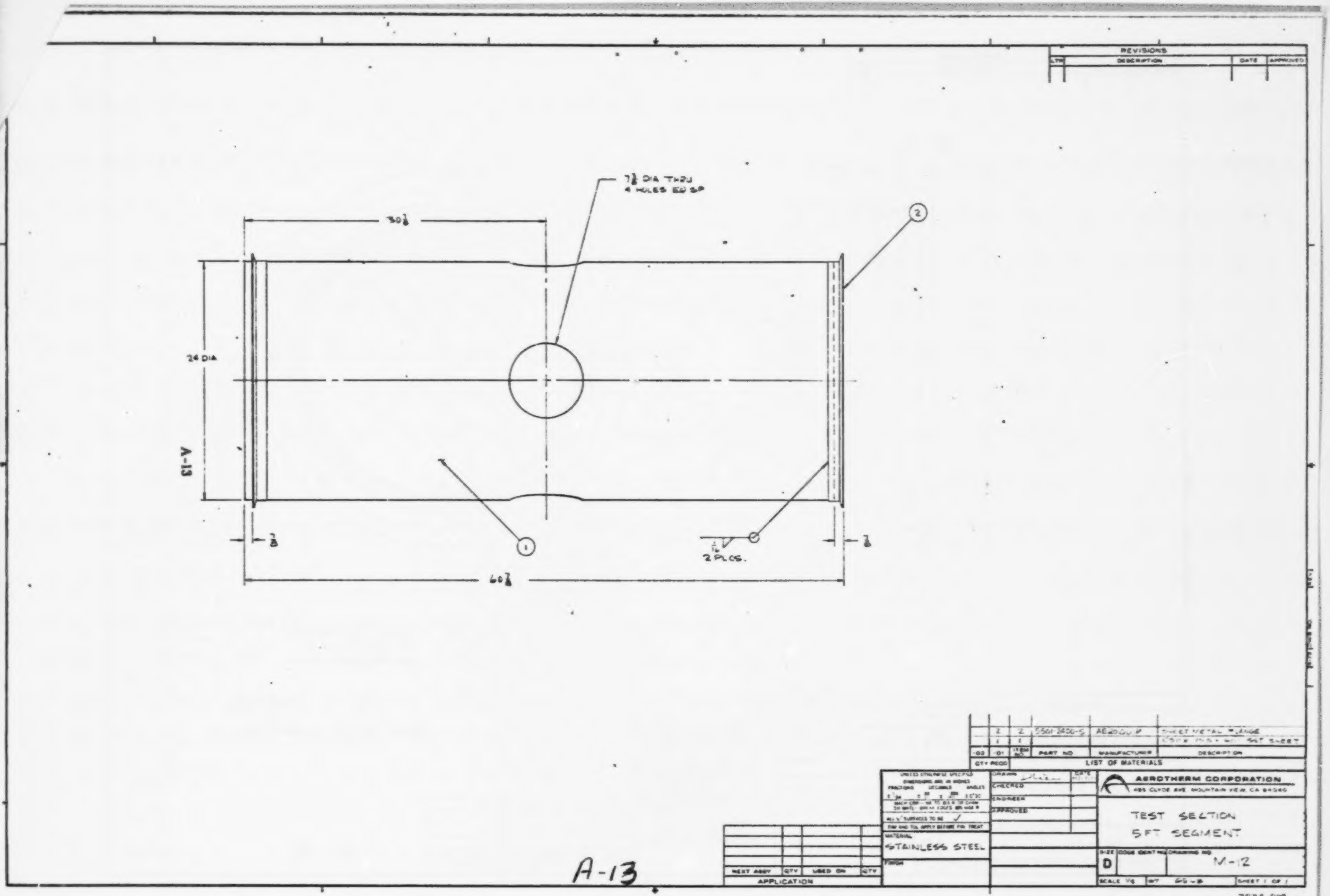
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
1
2
3
4
5
98
7
7⅞ DIA THRU
2 HOLES 180° APART
76¼ DIA
72" DIA
24 ½ DIA
.203 DIA THRU
8 HOLES EQ SP ON
7.875 DIA BC.
2 PLCS
6 SP @ 6" = 36
12
7 SP @ 6" = 42
R
P
N
M
L
K
J
H
G
F
E
D
C
B
A
95.579
89.519
83.518
77.569
71.523
65.866
58.989
52.112
37.443
30.452
24.111
18.025
12.003
6.000
0
ITEM - 3
9/32 DIA THRU
45 HOLES EQ SP
@ 8° APART ON
75.000 DIA BC.
4°
8° TYP
TOP
4°
72½ DIA
ITEM - 1
SCALE: 1/16
NEXT ASSY
QTY
USED ON
QTY
APPLICATION
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS DECIMALS ANGLES
ALL ✓ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN TREAT
MATERIAL
STAINLESS STEEL
FINISH
DRAWN
CHECKED
ENGINEER
APPROVED
DATE
AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94040
CONTRACTION DUCT
SIZE
D
CODE IDENT NO
DRAWING NO
M-1C
SCALE 1/8
WT
SHEET 1 OF

ITEM - ⑤ DIM	
LTR	DIM.
A-A	19.296
B-B	19.283
C-C	19.1737
D-D	18.977
E-E	18.350
F-F	17.261
G-G	15.327
H-H	10.866
J-J	9.008
K-K	7.847
L-L	7.107
M-M	6.708
N-N	6.528
P-P	6.458
R-R	6.432

LIST OF MATERIALS

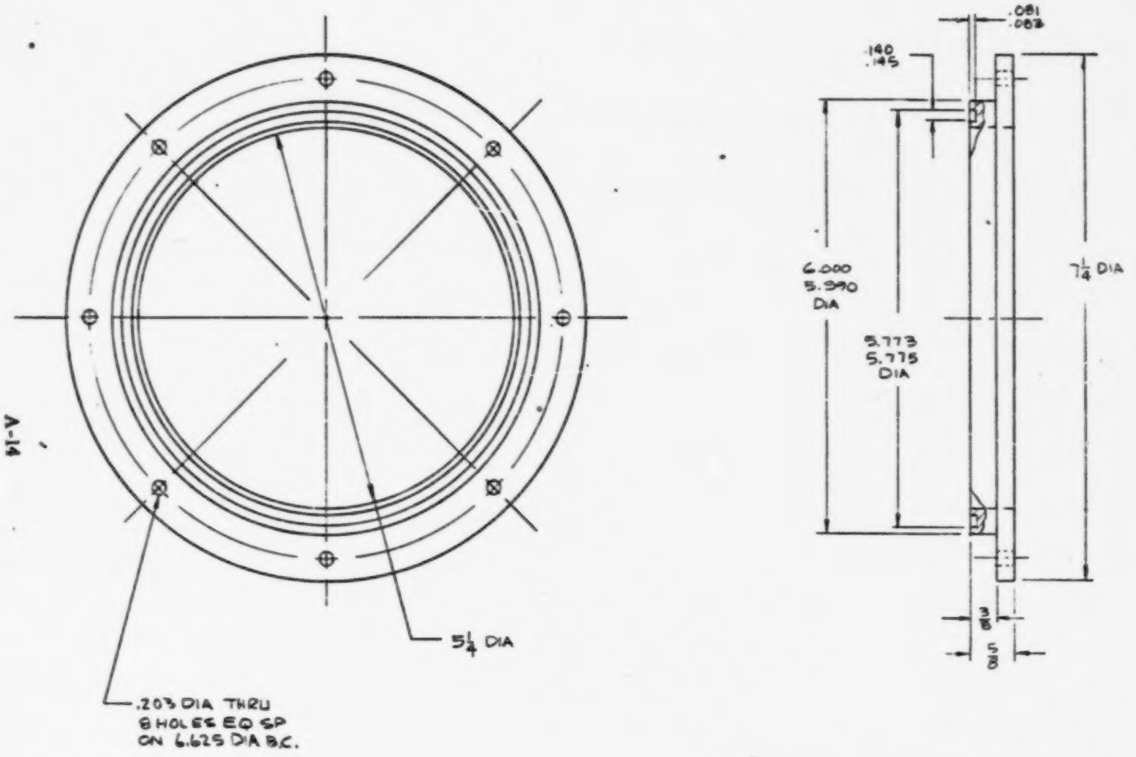
QTY REQD -02	QTY REQD -01	ITEM NO.	PART NO	MANUFACTURER	DESCRIPTION
	1	5	550LS-240-S	AEROQUIP	SHEET METAL FLANGE
	1	4			[illegible]
	12	3			
	1	2			[illegible]
		1			[illegible]


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
60 7/8
24 DIA
7/8
②
①
7 3/8 DIA THRU ON BOTH SIDES.
1/16
2 PLCS
7/8
120 7/8
2
2
5501-2400-5
SHEET METAL FLANGE
1
1
-02
-01
ITEM NO
PART NO
MANUFACTURER
DESCRIPTION
QTY REQD
LIST OF MATERIALS
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS
DECIMALS
ANGLES
±1°30'
MATERIAL
STAINLESS STEEL
FINISH
NEXT ASSY
QTY
USED ON
QTY
APPLICATION
DRAWN
CHECKED
ENGINEER
APPROVED
DATE
AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW CA 94040
TEST SECTION
10 FOOT SEGMENT
SIZE
D
CODE IDENT NO
DRAWING NO
M-11
SCALE 1/4
WT
SHEET 1 OF 1


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
7⅞ DIA THRU
4 HOLES EQ SP
30⅛
24 DIA
①
②
⅞
⅞
1/16
2 PLCS.
60⅛
2
2
5501-2400-5
AE20GUP
SHEET METAL FLANGE
1
1
-02
-01
ITEM NO
PART NO
MANUFACTURER
DESCRIPTION
QTY REQD
LIST OF MATERIALS
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS
DECIMALS
ANGLES
ALL SURFACES TO BE ✓
MATERIAL
STAINLESS STEEL
FINISH
DRAWN
DATE
CHECKED
ENGINEER
APPROVED
AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94040
TEST SECTION
5FT SEGMENT
SIZE
D
CODE IDENT NO
DRAWING NO
M-12
SCALE 1/8
WT
65 LB
SHEET 1 OF 1
NEXT ASSY
QTY
USED ON
QTY
APPLICATION

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED


5¼ DIA
.203 DIA THRU
8 HOLES EQ SP
ON 6.625 DIA B.C.
.081
.083
.140
.145
6.000
5.990
DIA
5.773
5.775
DIA
7¼ DIA
3/8
5/8

NOTES:

1. USE PARKER O-RING 2-162

A-14

-02	-01	ITEM NO.	PART NO.	MANUFACTURER	DESCRIPTION
QTY REQD		LIST OF MATERIALS			

NEXT ASSY	QTY	USED ON	QTY
APPLICATION			

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS ± 1/64 DECIMALS ± .XX .01 ± .XXX .005 ANGLES ± 0°30'
MACH COR— .005 TO .015 R OR CHAM
SH MATL—BREAK EDGES .005 MAX R
ALL √ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN TREAT
MATERIAL
303 STAINLESS
5/8 x 7¼ DIA
FINISH

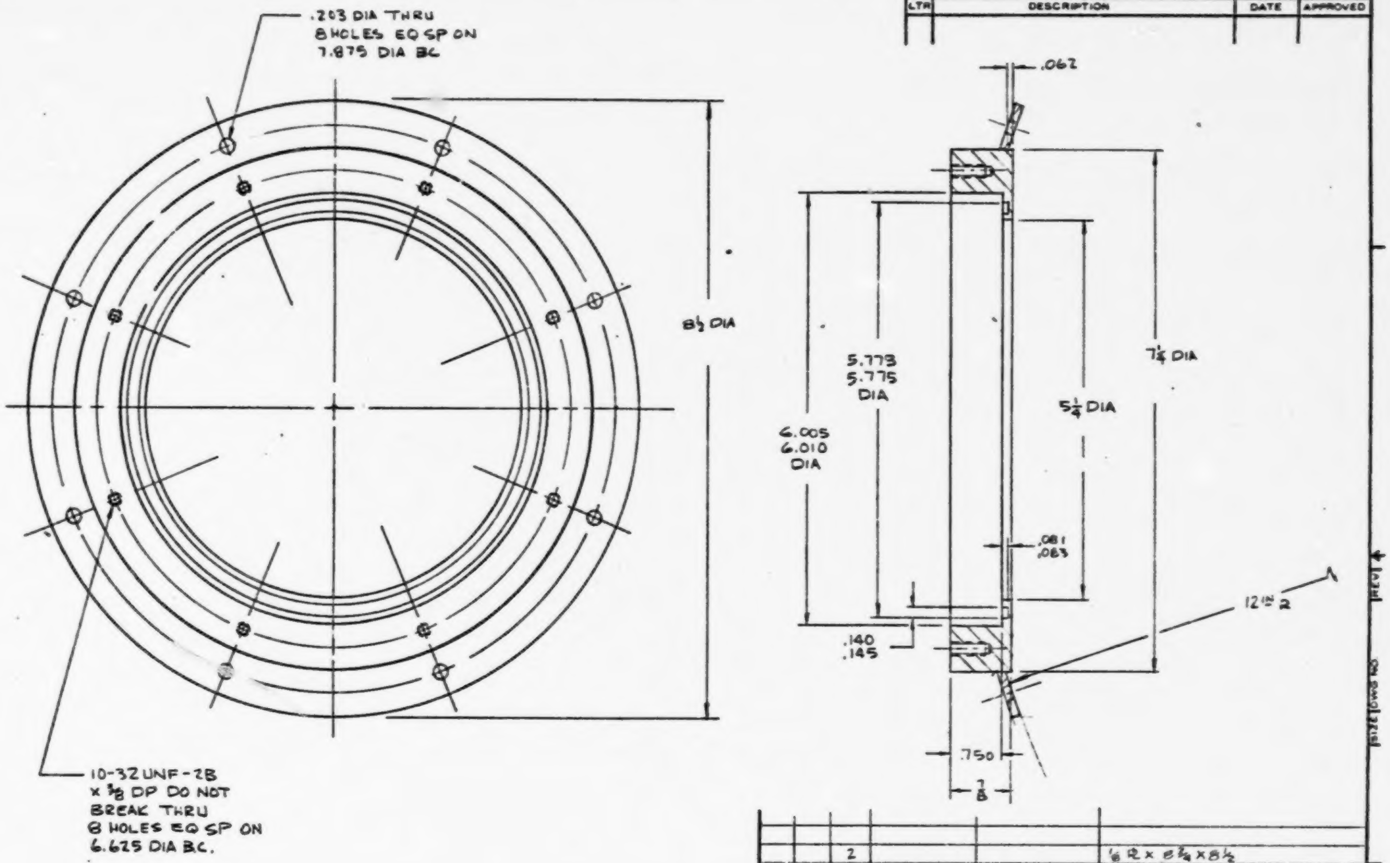
DRAWN DLJ DATE 8-27-71
CHECKED
ENGINEER
APPROVED

AEROTHERM CORPORATION
485 CLYDE AVE, MOUNTAIN VIEW, CA 94040

WINDOW CLAMP PLATE

SIZE C
CODE IDENT NO
DRAWING NO. M-13A
SCALE FULL
WT
SHEET 1 OF 1

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED


.203 DIA THRU
8 HOLES EQ SP ON
7.875 DIA BC
8½ DIA
10-32 UNF-2B
x ⅜ DP DO NOT
BREAK THRU
8 HOLES EQ SP ON
6.625 DIA B.C.
.062
6.005
6.010
DIA
5.773
5.775
DIA
5¼ DIA
7¼ DIA
.081
.083
12 IN 2
.140
.145
.750
7/8

NOTES:

1. USE PARKER O-RING 2-162

		2			⅛ R × 8¾ × 8½
		1			⅛ R × 7½ DIA
-02	-01	ITEM NO.	PART NO.	MANUFACTURER	DESCRIPTION
QTY REQD		LIST OF MATERIALS			

NEXT. ASSY	QTY	USED ON	QTY		
APPLICATION					

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS ± 1/64 DECIMALS ± .XX ± .XXX ANGLES ±0°30'
MACH COR — [illegible] TO .015 R OR CHAM
SH MATL — BREAK EDGES [illegible] MAX R
ALL √ SURFACES TO BE √
DIM AND TOL APPLY BEFORE FIN. TREAT.
MATERIAL 303 STAINLESS
FINISH

DRAWN	DATE
CHECKED	
ENGINEER	
APPROVED	

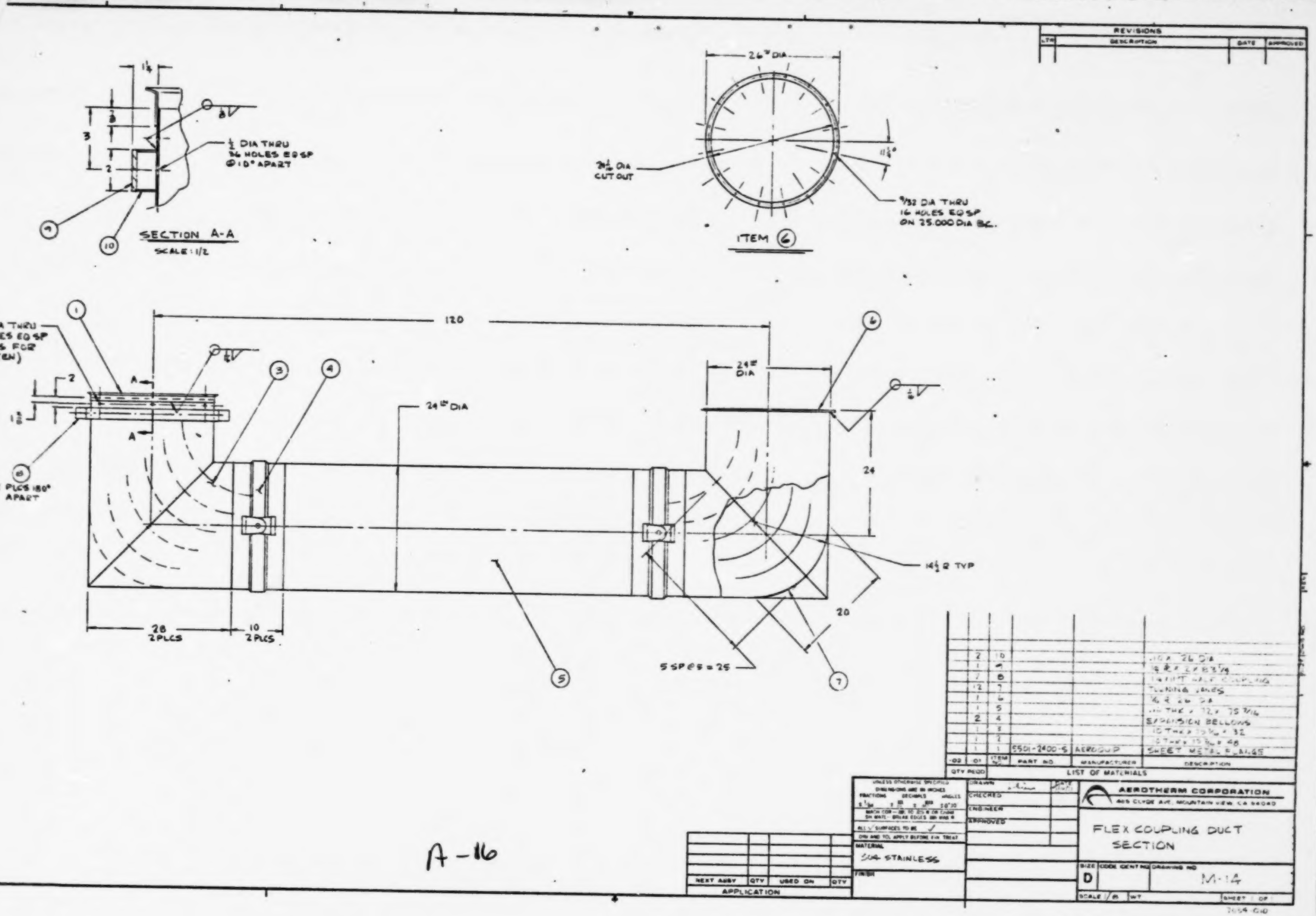
AEROTHERM CORPORATION
485 CLYDE AVE, MOUNTAIN VIEW, CA 94040

WINDOW FLANGE

SIZE	CODE IDENT NO	DRAWING NO.
C		M-13B

SCALE FULL WT SHEET 1 OF 1

7034-001


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
1¼
3
2
½ DIA THRU
36 HOLES EQ SP
@ 10° APART
9
10
SECTION A-A
SCALE: 1/2
26" DIA
3½ DIA
CUT OUT
11¼°
9/32 DIA THRU
16 HOLES EQ SP
ON 25.000 DIA BC.
ITEM ⑥
120
281 DIA THRU
6 HOLES EQ SP
(HOLES FOR
SCREEN)
1
2
A
A
3
4
6
24" DIA
24" DIA
24
8
2 PLCS 180° APART
14½ R TYP
28
2 PLCS
10
2 PLCS
5
20
5 SP @ 5 = 25
7
A-16

QTY REQD -02	QTY REQD -01	ITEM NO	PART NO	MANUFACTURER	DESCRIPTION
	2	10			.10 × 26 DIA
	1	9			1/8 × 2 × 83 1/4
	2	8			1 NPT HALF COUPLING
	12	7			TURNING VANES
	1	6			1/4 × 26 DIA
	1	5			.10 THK × 72 × 75 7/16
	2	4			EXPANSION BELLOWS
	1	3			.10 THK × 75 7/16 × 32
	1	2			.10 THK × 75 7/16 × 48
	1	1	5501-2400-5	AEROQUIP	SHEET METAL FLANGE

LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS ± 1/64 DECIMALS ± .XX ± .XXX ANGLES ± 0°30'
ALL ✓ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN. TREAT
MATERIAL
304 STAINLESS
FINISH

DRAWN
CHECKED
ENGINEER
APPROVED

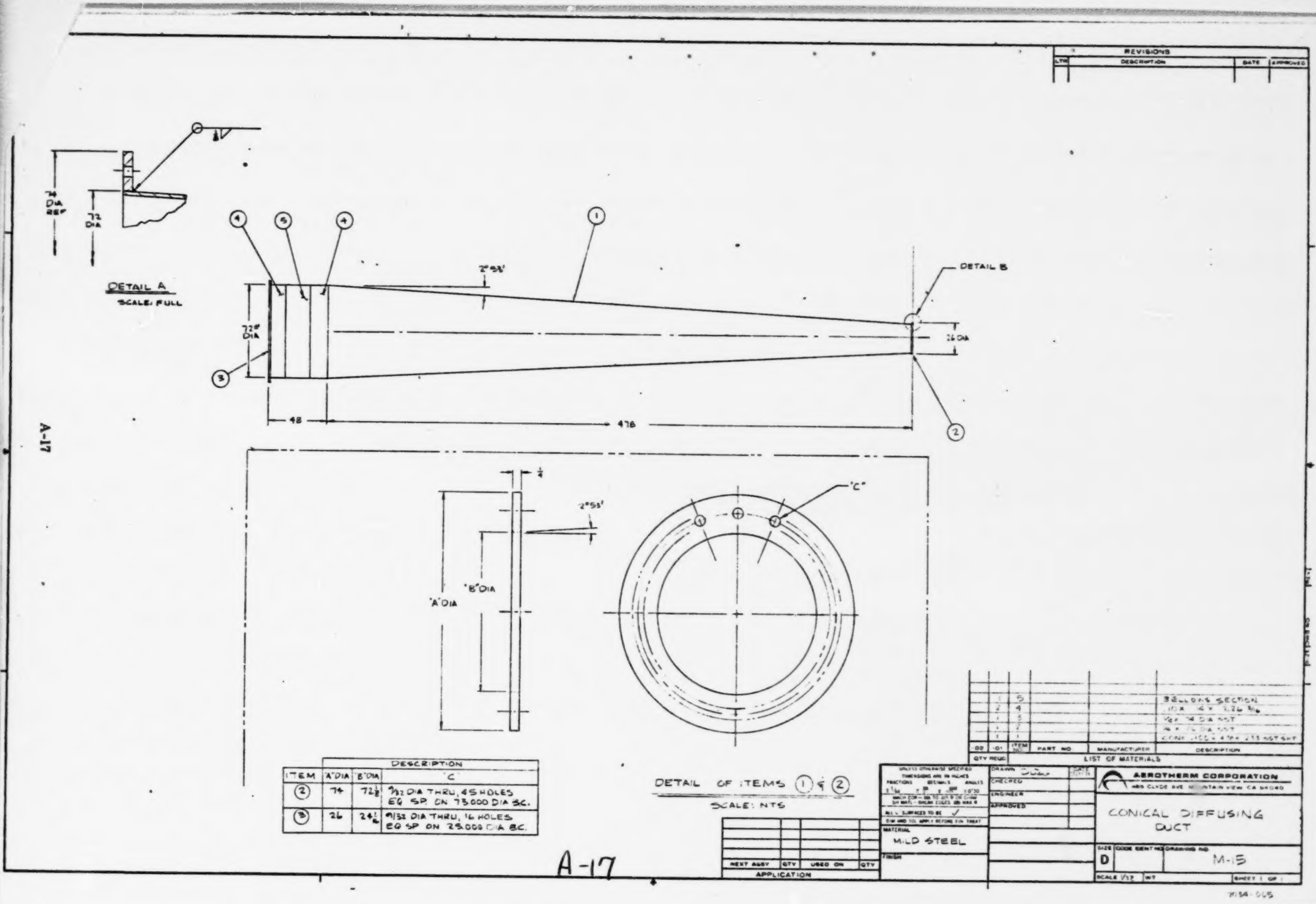
AEROTHERM CORPORATION
485 CLYDE AVE, MOUNTAIN VIEW, CA 94040

FLEX COUPLING DUCT
SECTION

SIZE D
CODE IDENT NO
DRAWING NO M-14
SCALE 1/8
WT
SHEET 1 OF 1

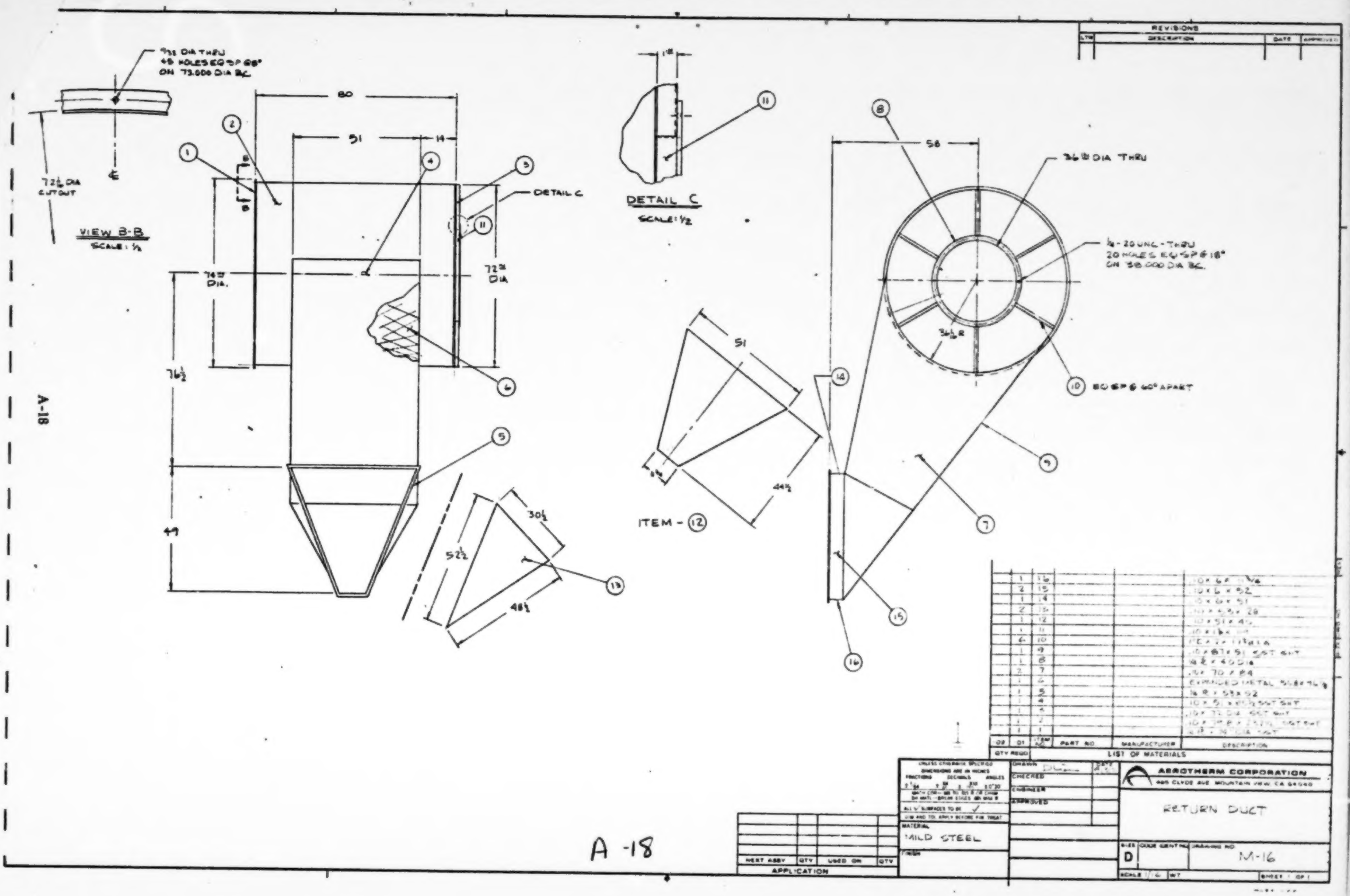
NEXT ASSY | QTY | USED ON | QTY
APPLICATION

7054-G10



REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
DETAIL A
SCALE: FULL
74 DIA REF
72 DIA
72" DIA
2°53'
DETAIL B
26 DIA
48
478
①
②
③
④
⑤
④
¼
2°53'
'B' DIA
'A' DIA
"C"
DETAIL OF ITEMS ① & ②
SCALE: NTS
BELLOWS SECTION
.10 x 4 x 3.26
1/4 x 74 DIA SST
1/4 x 76 DIA SST
CONE .100 x 47 x .33 SST SHT
-02
-01
ITEM NO
PART NO
MANUFACTURER
DESCRIPTION
QTY REQD
LIST OF MATERIALS
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS
DECIMALS
ANGLES
±1/64
±0°30
ALL SURFACES TO BE ✓
MATERIAL
MILD STEEL
FINISH
NEXT ASSY
QTY
USED ON
QTY
APPLICATION
DRAWN
CHECKED
ENGINEER
APPROVED
DATE
AEROTHERM CORPORATION
485 CLYDE AVE MOUNTAIN VIEW CA 94040
CONICAL DIFFUSING DUCT
SIZE
D
CODE IDENT NO
DRAWING NO
M-15
SCALE 1/12
WT
SHEET 1 OF 1
7134-015
A-17

ITEM	'A' DIA	'B' DIA	'C'
②	74	72 1/8	7/32 DIA THRU, 45 HOLES EQ SP. ON 73.000 DIA BC.
③	26	24 1/16	9/32 DIA THRU, 16 HOLES EQ SP ON 25.000 DIA BC.


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
9/32 DIA THRU
45 HOLES EQ SP @ 8°
ON 73.000 DIA BC
72⅛ DIA
CUTOUT
VIEW B-B
SCALE: ½
80
51
14
①
②
③
④
⑤
⑥
⑪
DETAIL C
74⅜ DIA.
72⅜ DIA
76½
49
30½
52½
48½
⑬
1⅛
DETAIL C
SCALE: ½
58
⑧
36⅜ DIA THRU
¼-20 UNC-THRU
20 HOLES EQ SP @ 18°
ON 38.000 DIA BC.
36½ R
⑩ EQ SP @ 60° APART
⑨
⑦
⑭
⑮
⑯
51
44½
ITEM - ⑫
A-18

QTY REQD 02	QTY REQD 01	ITEM NO	PART NO	MANUFACTURER	DESCRIPTION
	1	16			.10 × 6 × [illegible]
	2	15			.10 × 6 × 52
	1	14			.10 × 6 × 51
	2	13			.10 × 6⅝ × 28
	1	12			.10 × 51 × 45
	1	11			.10 × 1⅛ × [illegible]
	6	10			[illegible] × 2 × 11⅜ DIA
	1	9			.10 × 67 × 51 SST SHT
	1	8			¼ R × 40 DIA
	2	7			.10 × 70 × 84
	1	6			EXPANDED METAL 56⅛ × 76⅛
	1	5			¼ R × 53 × 52
	1	4			.10 × 51 × [illegible] SST SHT
	1	3			.10 × 72 DIA SST SHT
	1	2			.10 × [illegible] SST SHT
	1	1			[illegible] × 76 DIA SST

LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS ± 1/64 DECIMALS ± .XX ± .XXX ANGLES ± 0°30'
ALL ✓ SURFACES TO BE ✓
MATERIAL
MILD STEEL
FINISH

DRAWN DL
CHECKED
ENGINEER
APPROVED

AEROTHERM CORPORATION
485 CLYDE AVE MOUNTAIN VIEW CA 94040

RETURN DUCT

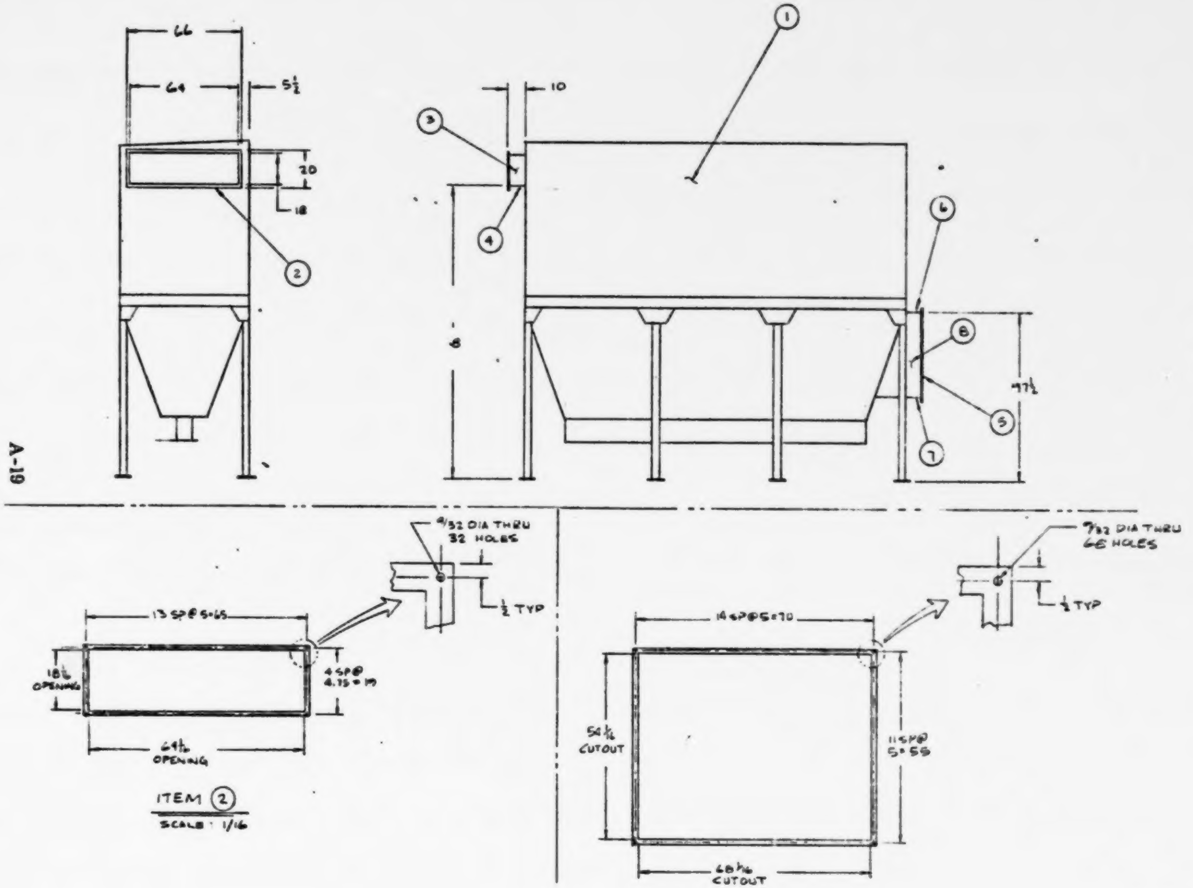
SIZE D
DRAWING NO M-16
SCALE 1/16
SHEET 1 OF 1

NEXT ASSY	QTY	USED ON	QTY

APPLICATION

A -18

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



66
64
5½
20
18
10
8
47½
49
①
②
③
④
⑤
⑥
⑦
⑧
9/32 DIA THRU 32 HOLES
½ TYP
13 SP@ 5=65
18½ OPENING
4 SP@ 4.75=19
64½ OPENING
9/32 DIA THRU 68 HOLES
½ TYP
14 SP@ 5=70
54½ CUTOUT
11 SP@ 5=55
68½ CUTOUT

ITEM ② SCALE: 1/16

ITEM ⑧ SCALE: 1/16

A-19

-02	-01	ITEM NO	PART NO	MANUFACTURER	DESCRIPTION
	1	8			10 x 57.6 x 28 SST
	1	7			10 x 1¾ x 28
	2	6			10 x 51 x 10
	1	5			¼ R 53 x 51
	2	4			10 x 66 x 10½
	2	3			10 x 78 x 10½
	1	2			¼ R 20 x 64 SST
	1	1	1F3	MIKROPUL	DUST COLLECTOR
QTY REQD		LIST OF MATERIALS			

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
FRACTIONS ± 1/64 DECIMALS ± .XX ± .XXX ANGLES ± 0°30'
MACH FOR — .XX TO .XX R OR CHAM; SH MATL — BREAK EDGES .XX MAX R
ALL ✓ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN TREAT
MATERIAL MILD STEEL INLET STAINLESS STEEL OUTLET
FINISH

DRAWN	Jim
CHECKED	
ENGINEER	
APPROVED	

AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94040

DUST COLLECTOR
MODIFICATION

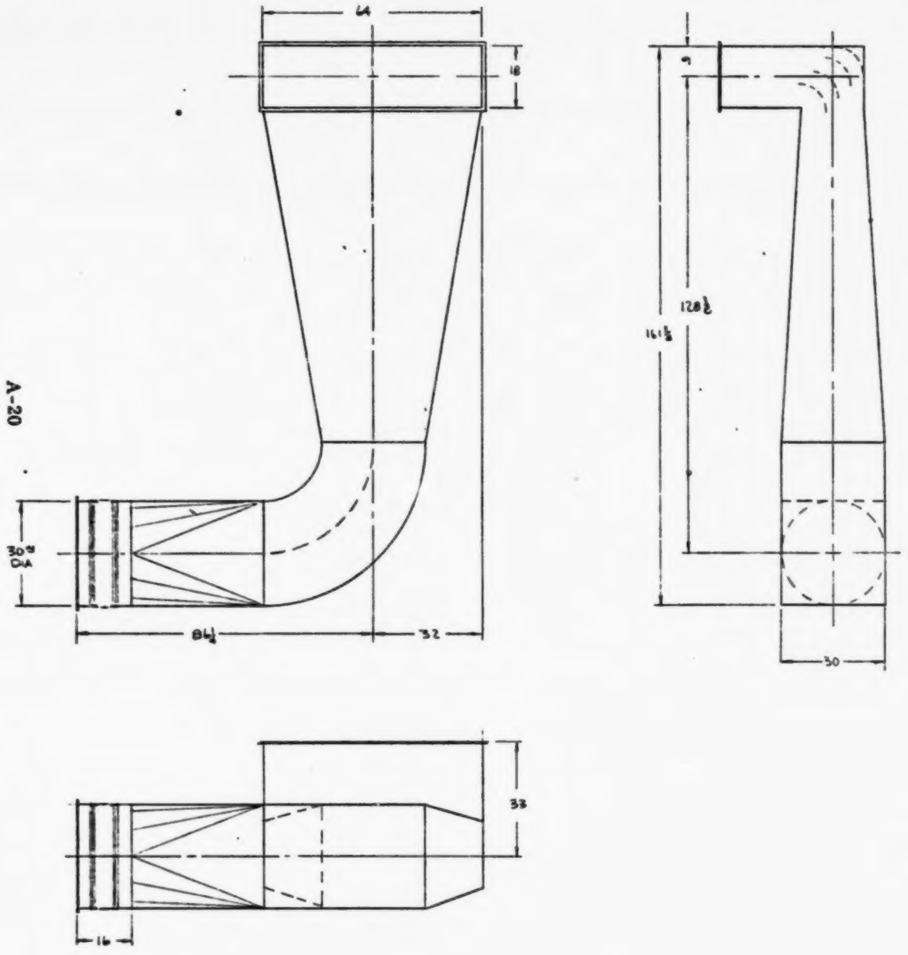
SIZE D | CODE IDENT NO | DRAWING NO M-17
SCALE 1/32 | WT | SHEET 1 OF 1

NEXT ASSY	QTY	USED ON	QTY
APPLICATION			

A-19

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED



·02	·01	ITEM NO	PART NO	MANUFACTURER	DESCRIPTION
QTY REQD		LIST OF MATERIALS			

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTIONS DECIMALS ANGLES
±1/64 [illegible] ±0°30'
[illegible]
ALL ✓ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN TREAT
MATERIAL
STAINLESS STEEL
FINISH

DRAWN Dl... DATE
CHECKED
ENGINEER
APPROVED

AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94040

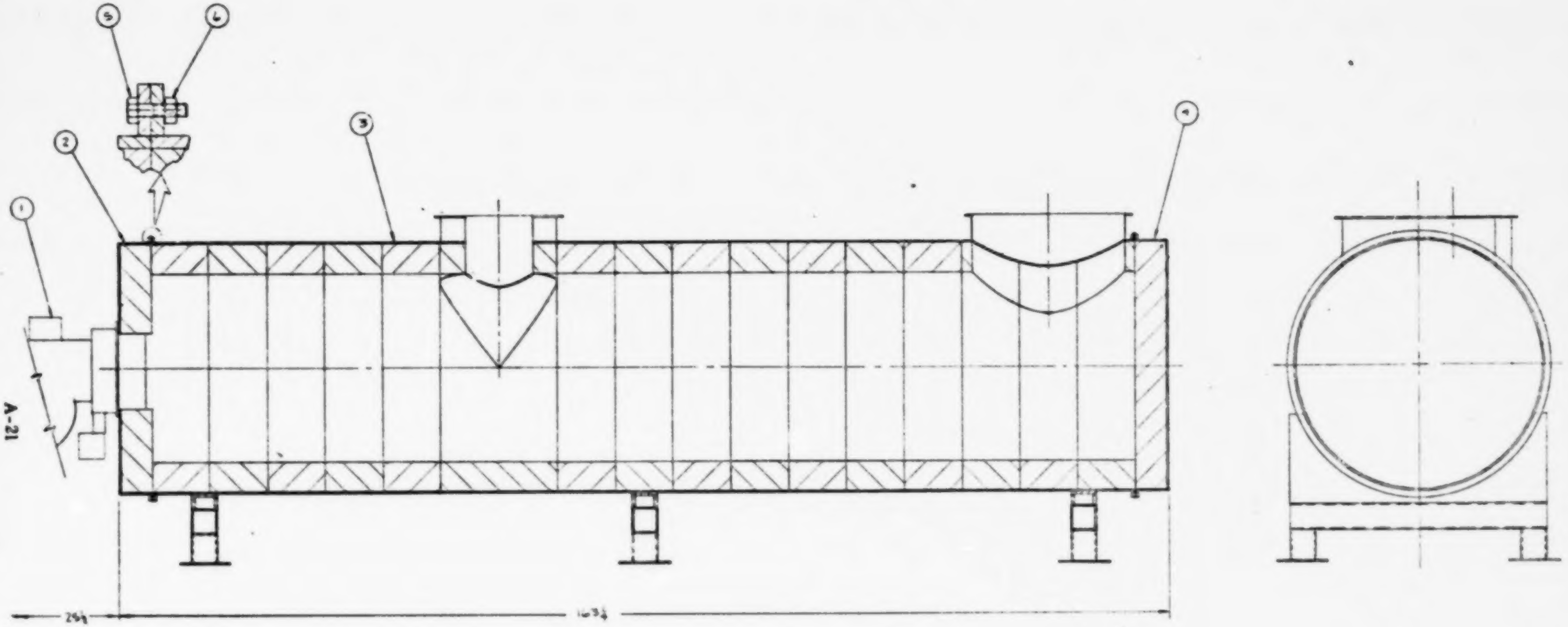
BAGHOUSE / BLOWER
DUCT

SIZE D
CODE IDENT NO
DRAWING NO M-18
SCALE 1/16
WT
SHEET 1 OF 1

NEXT ASSY	QTY	USED ON	QTY
APPLICATION			

7054 011

A-20



		6			1/4-20UNC HEX NUT
		5			1/4-20UNC BOLT x 1 1/4
	1	4			END CAP
	1	3			FURNACE
	1	2			BURNER SUPPORT CAP
	1	1	CHP-60-2	H.T. JOHNSON	BURNER
-02	-01	ITEM NO	PART NO	MANUFACTURER	DESCRIPTION
QTY REQD	LIST OF MATERIALS				

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED

AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94042

FURNACE ASSEMBLY

SIZE D | CODE IDENT NO | DRAWING NO M-19

SCALE 1/8 | WT | SHEET OF

DRAWN | CHECKED | ENGINEER | APPROVED | DATE

MATERIAL

FINISH

NEXT ASSY | QTY | USED ON | QTY

APPLICATION

TABLE 1

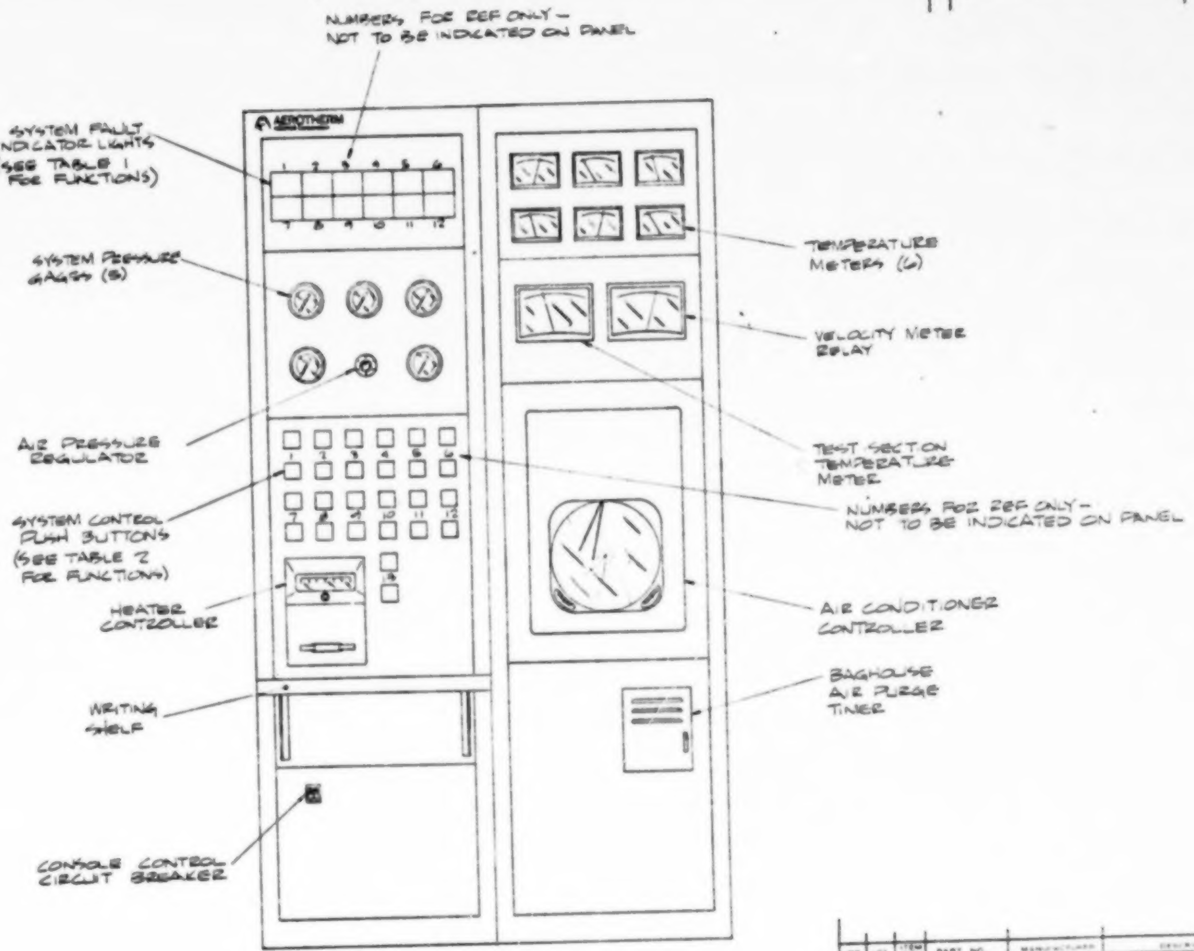
SYSTEM FAULT INDICATOR LIGHTS
(RED IF FAULT, GREEN IF NO FAULT)

1	FAN MOTOR - NO COOLING
2	FAN MOTOR - NO FAN ROTATION
3	FAN MOTOR - HIGH AIR TEMPERATURE
4	FAN MOTOR - VALVE SETTINGS
5	CHILLED WATER PUMP - NO FLOW
6	HUMIDIFIER - NO FLOW
7	DUCT HEATER - GAS VELOCITY
8	DUCT HEATER - OVERHEAT
9	BAGHOUSE - GAS TEMPERATURE
10	BURNER INTERLOCK
11	RESERVED FOR DUST FEEDER
12	RESERVED FOR DUST FEEDER

TABLE 2

SYSTEM CONTROL PUSH BUTTONS

1	DUCT BLOWER
2	DUCT HEATER
3	BURNER BLOWER
4	BURNER IGNITION
5	BAGHOUSE AIRLOCK
6	TUNNEL INLET VALVE
7.	DUST FEEDER BIN VIBRATOR
8	CHILLED WATER PUMP
9	BAGHOUSE SCREW CONVEYOR
10	TUNNEL EXHAUST VALVE
11	TUNNEL OPEN CIRCUIT VALVE
12	DILUTION AIR VALVE
13	FIREBOX EXHAUST VALVE


NUMBERS FOR REF ONLY - NOT TO BE INDICATED ON PANEL
AEROTHERM
1 2 3 4 5 6
7 8 9 10 11 12
SYSTEM FAULT INDICATOR LIGHTS (SEE TABLE 1 FOR FUNCTIONS)
SYSTEM PRESSURE GAGES (5)
AIR PRESSURE REGULATOR
SYSTEM CONTROL PUSH BUTTONS (SEE TABLE 2 FOR FUNCTIONS)
HEATER CONTROLLER
WRITING SHELF
CONSOLE CONTROL CIRCUIT BREAKER
TEMPERATURE METERS (6)
VELOCITY METER RELAY
TEST SECTION TEMPERATURE METER
NUMBERS FOR REF ONLY - NOT TO BE INDICATED ON PANEL
AIR CONDITIONER CONTROLLER
BAGHOUSE AIR PURGE TIMER

REVISIONS

LIST OF MATERIALS

DRAWN Boyd

CHECKED

ENGINEER

APPROVED

MATERIAL

FINISH

NEXT ASSY | QTY | USED ON | QTY

APPLICATION

AEROTHERM CORPORATION

CONTROL CONSOLE ASSEMBLY

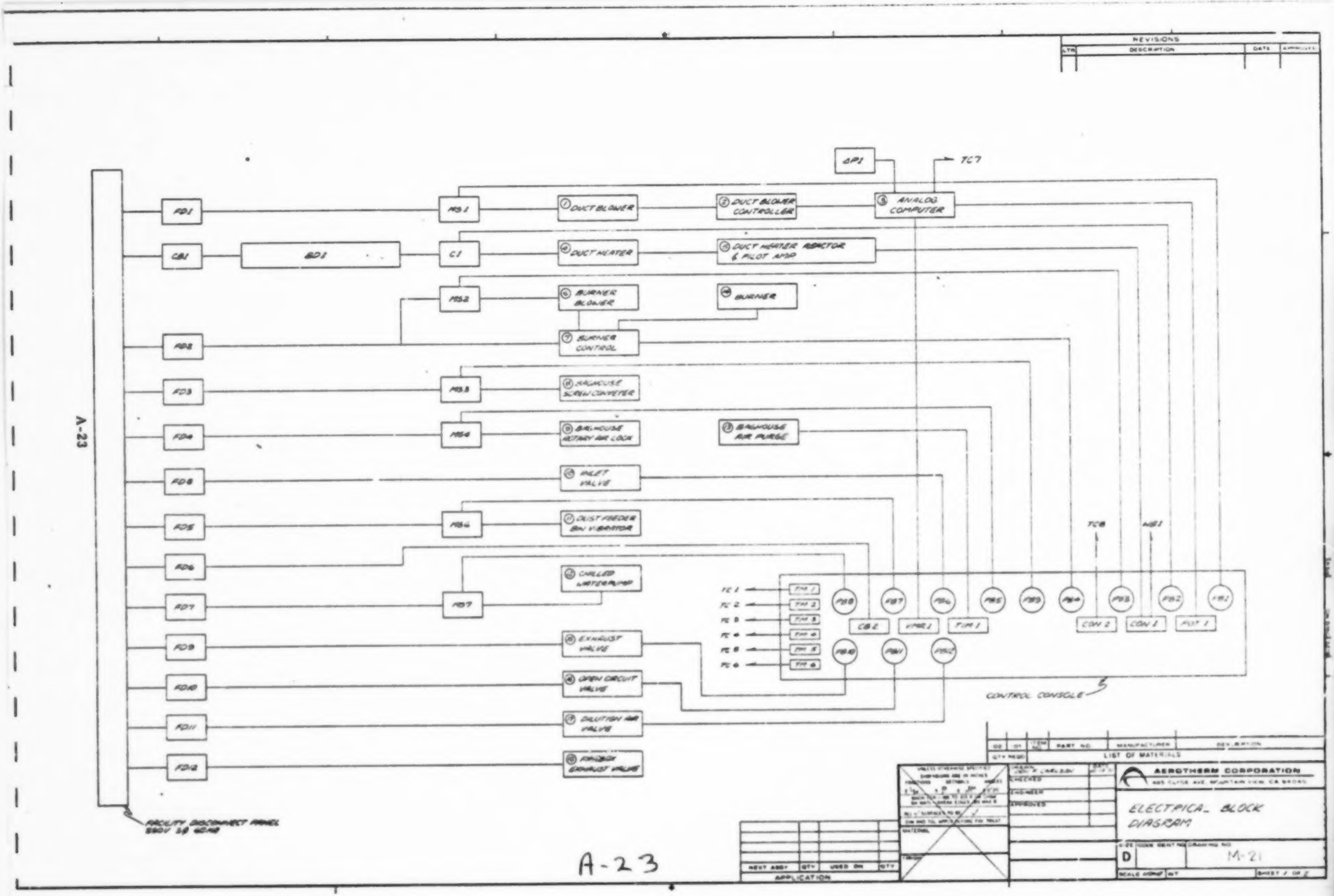
SIZE D

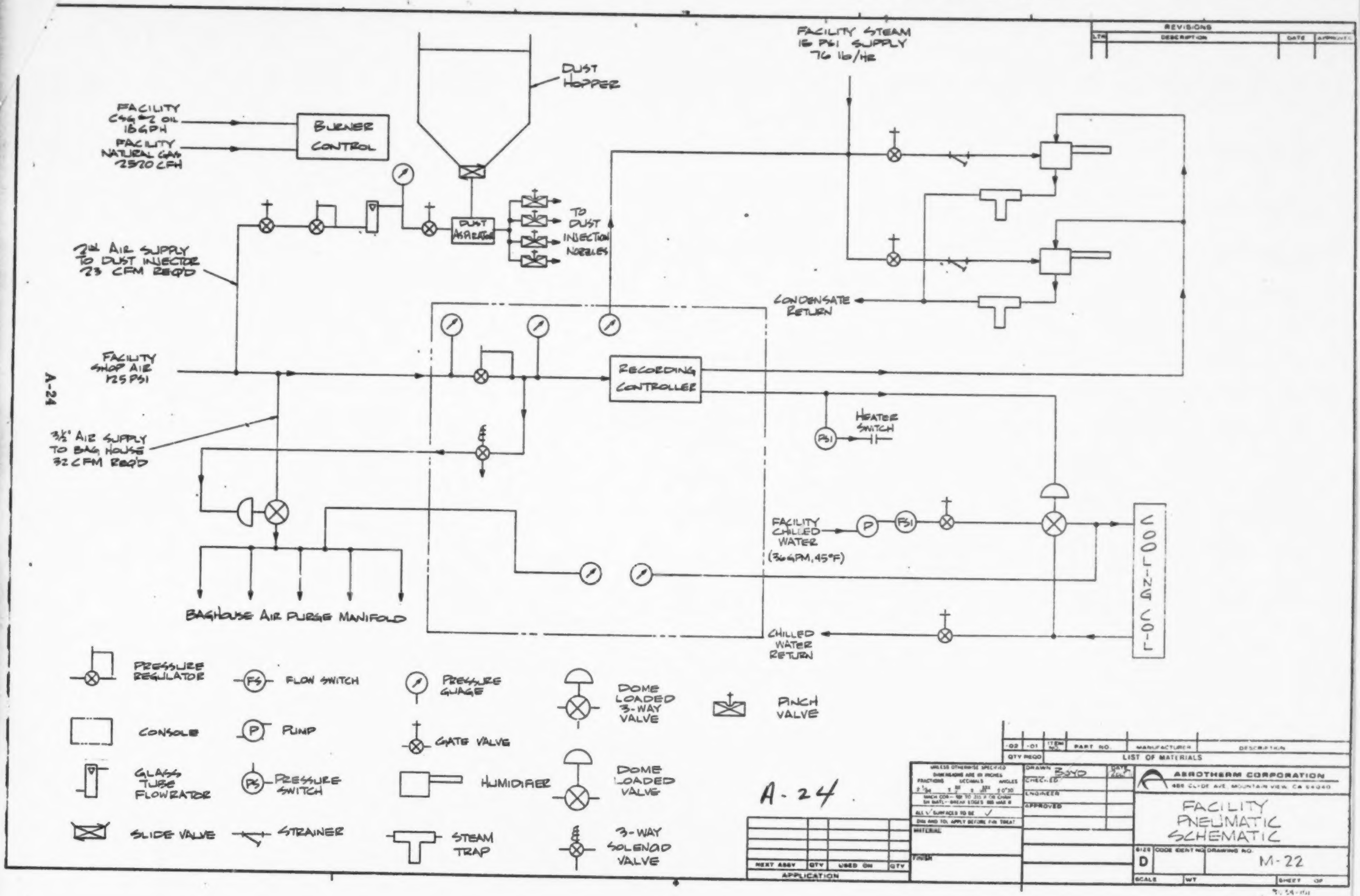
DRAWING NO. M-20

SCALE

WT

SHEET OF


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A-23
FACILITY DISCONNECT PANEL
FD1
CB1
SD1
FD2
FD3
FD4
FD8
FD5
FD6
FD7
FD9
FD10
FD11
FD12
MS1
C1
MS2
MS3
MS4
MS6
MS7
DUCT BLOWER
DUCT HEATER
BURNER BLOWER
BURNER CONTROL
BAGHOUSE SCREW CONVEYER
BAGHOUSE ROTARY AIR LOCK
INLET VALVE
DUST FEEDER BIN VIBRATOR
CHILLED WATER PUMP
EXHAUST VALVE
OPEN CIRCUIT VALVE
DILUTION AIR VALVE
EXHAUST VALVE
DUCT BLOWER CONTROLLER
DUCT HEATER REACTOR & PILOT AMP
BURNER
BAGHOUSE AIR PURGE
ΔP1
ANALOG COMPUTER
TC7
TC8
WB1
TC1
TC2
TC3
TC4
TC5
TC6
TM1
TM2
TM3
TM4
TM5
TM6
PB8
PB7
PB6
PB5
PB9
PB4
PB3
PB2
PB1
CB2
VMR1
TIM1
CON2
CON1
POT1
PB10
PB11
PB12
CONTROL CONSOLE
QTY REQD
ITEM NO.
PART NO.
MANUFACTURER
DESCRIPTION
LIST OF MATERIALS
CHECKED
ENGINEER
APPROVED
MATERIAL
NEXT ASSY
QTY
USED ON
APPLICATION
AEROTHERM CORPORATION
ELECTRICAL BLOCK DIAGRAM
SIZE
D
DRAWING NO.
M-21
SCALE
SHEET 1 OF 2


FACILITY C4&2 OIL 16GPH
FACILITY NATURAL GAS 2520 CFH
BURNER CONTROL
DUST HOPPER
DUST ASPIRATOR
TO DUST INJECTION NOZZLES
2" AIR SUPPLY TO DUST INJECTOR 23 CFM REQ'D
FACILITY SHOP AIR 125 PSI
3½" AIR SUPPLY TO BAG HOUSE 32 CFM REQ'D
BAGHOUSE AIR PURGE MANIFOLD
RECORDING CONTROLLER
FACILITY STEAM 16 PSI SUPPLY 76 lb/HR
CONDENSATE RETURN
HEATER SWITCH
PSI
FACILITY CHILLED WATER (36 GPM, 45°F)
P
FSI
COOLING COIL
CHILLED WATER RETURN
PRESSURE REGULATOR
CONSOLE
GLASS TUBE FLOWRATOR
SLIDE VALVE
FS
FLOW SWITCH
P
PUMP
PS
PRESSURE SWITCH
STRAINER
PRESSURE GUAGE
GATE VALVE
HUMIDIFIER
STEAM TRAP
DOME LOADED 3-WAY VALVE
DOME LOADED VALVE
3-WAY SOLENOID VALVE
PINCH VALVE
A-24
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
-02
-01
ITEM NO.
PART NO.
MANUFACTURER
DESCRIPTION
QTY REQD
LIST OF MATERIALS
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
FRACTIONS
DECIMALS
ANGLES
ALL ✓ SURFACES TO BE ✓
MATERIAL
FINISH
DRAWN Boyd
CHECKED
ENGINEER
APPROVED
DATE
AEROTHERM CORPORATION
485 CLYDE AVE. MOUNTAIN VIEW, CA 94040
FACILITY PNEUMATIC SCHEMATIC
SIZE D
CODE IDENT NO.
DRAWING NO. M-22
SCALE
WT
SHEET OF
NEXT ASSY
QTY
USED ON
QTY
APPLICATION